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Nonlinear Response of Carbon-Carbon Composite Panels Subjected to Thermal-acoustic Loadings

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Abstract. Carbon-Carbon composite materials are widely used as the surface thermal protection systems (TPS) of advanced high-speed air-craft and spacecraft. The thin-walled structures with this kind of materials would exhibit large displacement response under high-level acoustic loads and possibly display buckling at elevated temperatures. Reliable experimental data are difficult to acquire because of the high costs and difficulties with instrumentation at high acoustic intensity and elevated temperatures. Thus, in the design process greater emphasis will likely be placed on improved mathematical and computational prediction methods. Among these researches, the simulation methods for nonlinear response of thin-walled composite panels under thermo-acoustic loadings are being developed emphatically .This paper presents a nonlinear finite element model for analyzing nonlinear random dynamic behaviors of Carbon-Carbon composite panels under the combined effects of thermal and random acoustic loads. The acoustic excitation is assumed to be a band-limited Gaussian random noise and uniformly distributed over the structural surface and the thermal load is assumed to be a steady-state with different predefined temperature distribution. Three types of motion: 1) linear random vibration about one of the two buckled positions, 2) snap-through motion between the two buckled positions, and 3) nonlinear random vibration over the two thermally buckled positions can be predicted. And the dynamic response behaviors of the structures are discussed. Based on this, the influences of sound pressure level (SPL) and elevated temperatures on the dynamic responses are analyzed emphatically.

Introduction

Stochastically excited linear systems have been studied in great detail and numerous analytical techniques exist for both stationary and non-stationary problems. Unfortunately, the majority of structural responses are nonlinear and not many techniques exist for the analysis. There are five major analysis methods for the prediction of nonlinear response of structures available 1) perturbation, in this approximate method, the stochastically exited nonlinear system is treated as a deterministically excited system and was applied to a continuous nonlinear system by Lyon [1] and to discrete nonlinear systems by Crandall [2]. The perturbation approximation; however, will not give accurate result for systems of large nonlinearity and is limited to weak geometric nonlinearities. 2) Fokker Plank Kolmogorov (FPK equation), The FPK equations approaches give an exact solution for a restricted class of simple problems. In general, the transitional Probability Density Function (PDF) cannot be found with the FPK equation approach. Without this transitional probability, it is generally impossible to obtain the correlation function and Power Spectral Density (PSD) of the response. The difficulty in dealing exactly with solutions of stochastically excited nonlinear systems has led to and intensified effort to develop approximate methods, to tackle a broader class of problems than presently possible with the exact analysis. 3) Monte Carlo, this method is the most general method, but the use of partial differential equation and Galerkin's approach limits its applicability to rather simple structures. 4) Equivalent linearization (EL), this method has been widely applied because of their ability to capture accurately the response statistics over a wide range of response while maintaining a relatively light computational burden. The draw back of the equivalent linearization technique is the assumption that the response has to be Gaussian and 5) Numerical Simulation

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Approaches, This approach can be used for estimating the response statistics, calculating the corresponding response samples, and processing the desired response statistics. Obviously, this approach can be used for estimating the response statistics of both stationary and non-stationary excitations. The major drawback of this approach is the computation time and cost.

Composite panel was first studied by Mei and Chen uses the FE/EL solution procedure [3]. The FE/EL method, therefore, does not give accurate predictions for snap-through (or oil-canning) and large-amplitude nonlinear random motions. Experiments by Ng and Clevenson [4], IStennes et al [5], and Murphy et al [6, 7] have shown that the dynamic response of acoustic excited thermally buckled plates may exhibit the following two types of motion: (i) small amplitude vibrations about one of the coexisting static equilibriums, and (ii) large amplitude nonlinear snap-through oscillations between and over the two post buckling positions.

This paper presents a nonlinear finite element model for modeling nonlinear random dynamic behaviors of Carbon-Carbon composite panels under the combined effects of thermal and random acoustic loads. The acoustic excitation is assumed to be a band-limited Gaussian random noise and uniformly distributed over the structural surface and the thermal load is assumed to be a steady-state with different predefined temperature distribution. All of the three types of motion 1) linear random vibration about one of the two buckled positions, 2) snap-through motion between the two buckled positions, and 3) nonlinear random vibration over the two thermally buckled positions can be predicted. And dynamic response under different Sound Pressure Lever (SPL) and temperature are discussed respectively.

Finite Element Formulation

The element displacements are expressed in terms of the node DOF as

$$\mathrm{u}(x,y,t)=\left|H_u\right|\left\{w_m\right\} \tag{1}$$

$$v(x,y,t)=\left|H_v\right|\left\{w_m\right\} \tag{2}$$

$$w(x,y,t)=\left|H_w\right|\left\{w_b\right\} \tag{3}$$

Where u , v and w are the in-plane and transverse displacement of the middle surface; the vectors $\{w_m\}$ and $\{w_b\}$ denote the in-plane and bending node DOF; and $\left|H_u\right|, \left|H_v\right|$ and $\left|H_w\right|$ denote in-plane and transverse displacement functions, respectively.

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial u}{\partial x} \\ \dfrac{\partial v}{\partial y} \\ \dfrac{\partial u}{\partial y}+\dfrac{\partial v}{\partial x} \end{Bmatrix} + \begin{Bmatrix} \dfrac{1}{2}\left(\dfrac{\partial w}{\partial x}\right)^2 \\ \dfrac{1}{2}\left(\dfrac{\partial w}{\partial y}\right)^2 \\ \dfrac{\partial w}{\partial x}\dfrac{\partial w}{\partial y} \end{Bmatrix} + \mathrm{Z}\begin{Bmatrix} \dfrac{\partial \phi_y}{\partial x} \\ \dfrac{\partial \phi_x}{\partial y} \\ \dfrac{\partial \phi_y}{\partial y}+\dfrac{\partial \phi_x}{\partial x} \end{Bmatrix} = \left\{\varepsilon_{lin}\right\}+\left\{\varepsilon_{\theta}\right\}+\mathrm{Z}\left\{\kappa\right\} \tag{4}$$

Where $\{\varepsilon^0\}$ and $\{\kappa\}$ denote the in-plane strain and curvature strain vectors; and $[\theta]$ is the slope matrix respectively.

The stress-strain constitutive relations for the k th lamina with a general orientation angle and a temperature change are

$$\{\sigma\}_k = \begin{bmatrix} Q_{11} & Q_{12} & Q_{16} \\ Q_{21} & Q_{22} & Q_{26} \\ Q_{61} & Q_{62} & Q_{66} \end{bmatrix}_K \left(\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} - \Delta T \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{Bmatrix} \right) = \left[\overline{Q}\right]_k \left(\{\varepsilon\} - \Delta T \{\alpha\}_k\right) \tag{5}$$

Where $\left[\overline{Q}\right]_k$ the transformed reduced stiffness matrix and $\{\alpha\}_k$ is the thermal expansion coefficient vector.

Using the principle of virtual work, the governing equations for a composite plate under the combined action of thermal and random acoustic loads can be stated in a compact form as

$$[M]\{\ddot{w}\} + \left([K] - [K_t] + [K_r] + \frac{1}{2}[N_1] + \frac{1}{3}[N_2]\right)\{w\} = \{P(t)\} + \{P_T\} - \{P_r\} \tag{6}$$

Where $[K]$ $[K_t]$ and $[K_r]$ are the linear, thermal, and recovery-stress stiffness matrices respectively; $[N_1]$ and $[N_2]$ are the first and second-order nonlinear stiffness matrices; K is a shear correction factor; and $\{P_T\}$ are the thermal and $\{P_r\}$ is the recovery-stress vectors. Eq. 6 is solved by using a truncated Taylor series expansion and the Newton-Raphson iteration procedure method in this paper.

Numerical Results and Discussions

The plate nonlinear random vibration under acoustic and thermal loads is investigated with two parameters in the study: temperature rise ΔT . And sound pressure level SPL. The acoustic excitation is assumed to be a band-limited Gaussian random noise and uniformly distributed over the structural surface and the thermal load is assumed to be a steady-state with different predefined temperature distribution. A rectangular composite plate with dimension of 0.2by0.26by0.00125m and five layers [90/45/0/45/90] (h=0.00025m/layer) is investigated in this paper, the test plate model and material properties are list as Fig. 1 and Table 1.

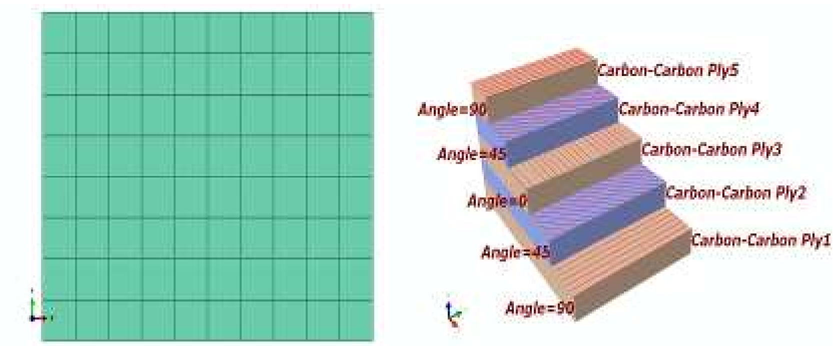


Fig. 1. Numerical model and layer angle of Carbon-Carbon composite plate

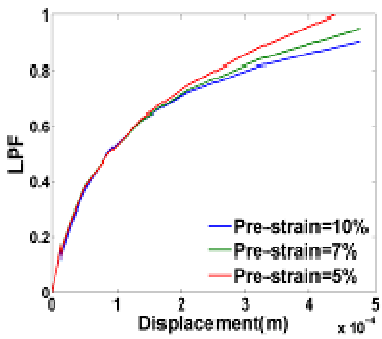


Fig. 2. LPF-Displacement curve with different pre-strain values

A proportional damping ratio with ξ=0.01 is used. The plate is modeled with a 6by6 mesh quarter plate and S8R element type which means 8 nodes of hexahedral with linear reduced integration shell element. The Newton-Raphson iteration scheme is adopted to solve the nonlinear algebraic system of equations at a time step of 1/10000.

Table 1. Material properties of the composite materials plate

E_2 [GPa]	E_2 [GPa]	$G_{12}=G_{13}$ [GPa]	G_{13} [GPa]	ρ [kg/ m^3]	ν	α_1 [ΔT/ $^\circ$C]	α_2 [ΔT/ $^\circ$C]
170	11	5	2.75	1430	0.31	8.5x10^{-5}	7.95x10^{-5}

A. Nonlinear buckling behavior. Fig. 2 presents the Load Proportional Factor (LPF) about Displacement relations which show the deflection and load relations during whole buckling process. The bifurcation of three lines stands for the buckling critical situation. It can be found that the buckling temperature keeps the same for different pre-strain; however, the post-buckling behaviors of the panel differ obviously. The same LPF increment corresponding with different deflection increment after the bifurcation point, the greater pre-strain with greater deflection increment which can means it will become more unstable after buckle than plate with smaller pre-stain.

B. Panel response under combined thermal and random acoustic loads. The plate nonlinear random vibration behavior is investigated with two parameters in the study: temperature rise ΔT and sound pressure level SPL, where ΔT varies from 0.5 to $10\,^{\circ}C$, and SPL varies from 140 to 165 dB. The acoustic excitation is assumed to be a band-limited Gaussian random noise with frequency range from 0 to 1500Hz and uniformly distributed over the structural surface. The thermal load is assumed to be a steady-state with different predefined temperature distribution. The total load time is 0.8125s and the Newton-Raphson iteration scheme is adopted to solve the nonlinear algebraic system of equations at each time step.

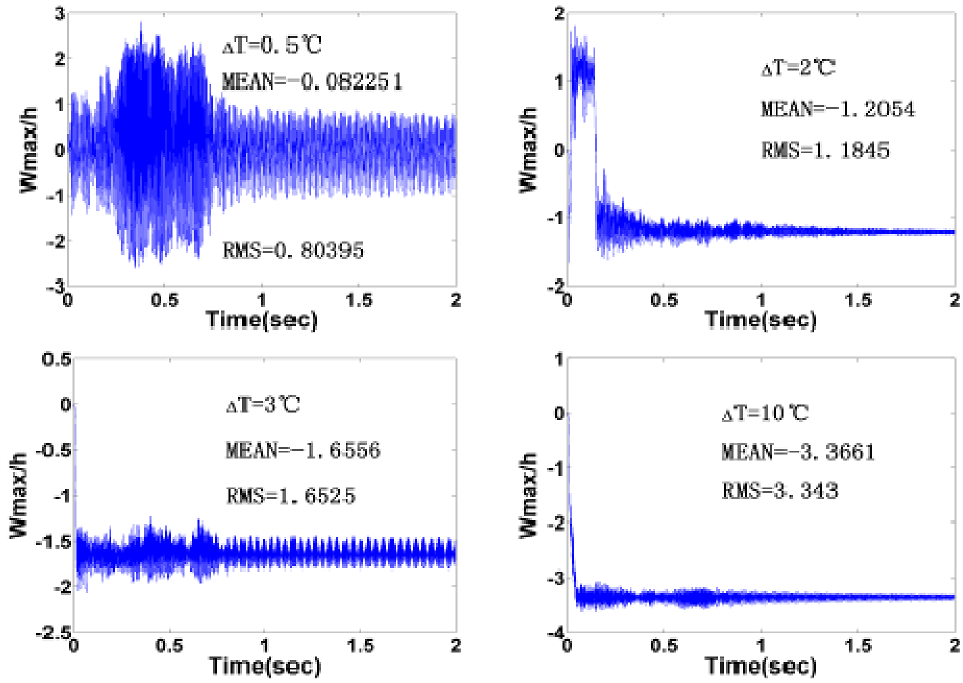


Fig. 3. Random vibration response of a clamped traditional composite plate at SPL=140dB and various temperature rise ΔT.

Fig. 3 presents the time-history response of a clamped Carbon-Carbon composite panel at SPL=140db and temperature rises of 0.5, 2, 3, $10\,^{\circ}C$. It can be seen that at temperature rise of $0.5\,^{\circ}C$ the plate exhibits basically small deflection random vibration, at temperature rise of $2\,^{\circ}C$ the plate experience large amplitude nonlinear snap-through oscillations between and over the two post buckling positions and then turned to small deflection random vibration about one of the two thermally buckled equilibrium positions when the temperature rise to $3\,^{\circ}C$ and above. It is also noticed that the thermally buckled equilibrium amplitude (absolute of MEAN show in Fig.3) and vibration deflection increases with temperature rise. This is mainly because with the temperature beyond the critical buckling temperature ΔT_{cr} [8] ($\Delta T_{cr} = 0.99\,^{\circ}C$), the thermal expansion dominates the recovery stress.

Fig. 4 presents the time-history response of a clamped panel at SPL=145dB. The plate exhibits a random vibration at $\Delta T = 0.5^{\circ}C$ and experiences a continuous snap-through at $\Delta T = 2^{\circ}C$ because the nonlinear stiffness has not yet compensated the critically lowered stiffness due temperature rise. With the temperature rise it turn to be small deflection random vibration about one of the two thermally buckled equilibrium positions again, the occurrence of snap-through is raised by the stiffness added by the increased thermal post buckling deflection, resulting completely hindering snap-through motions.

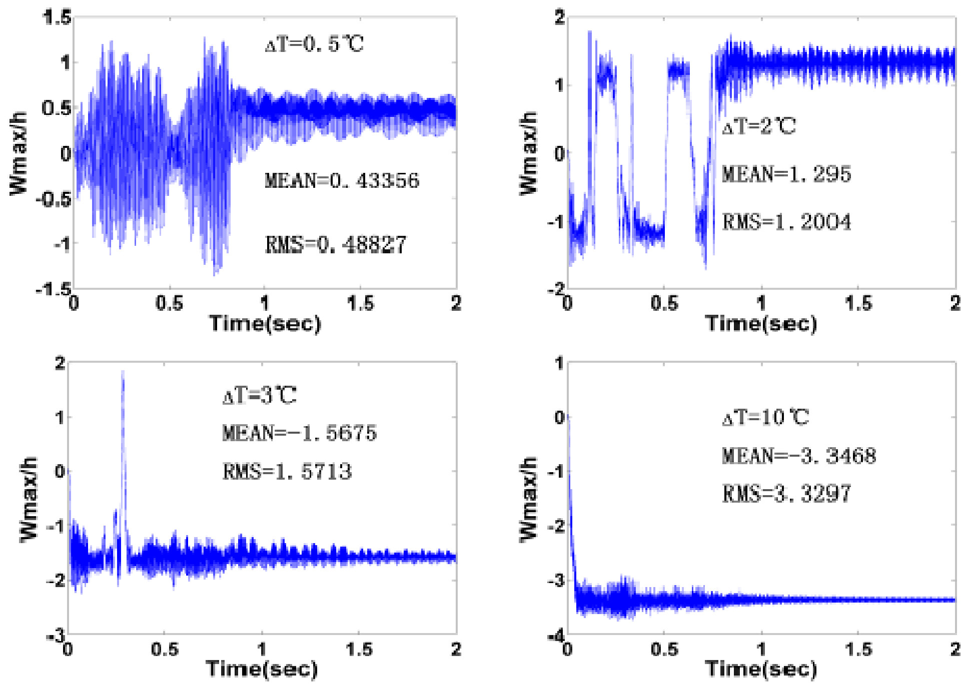
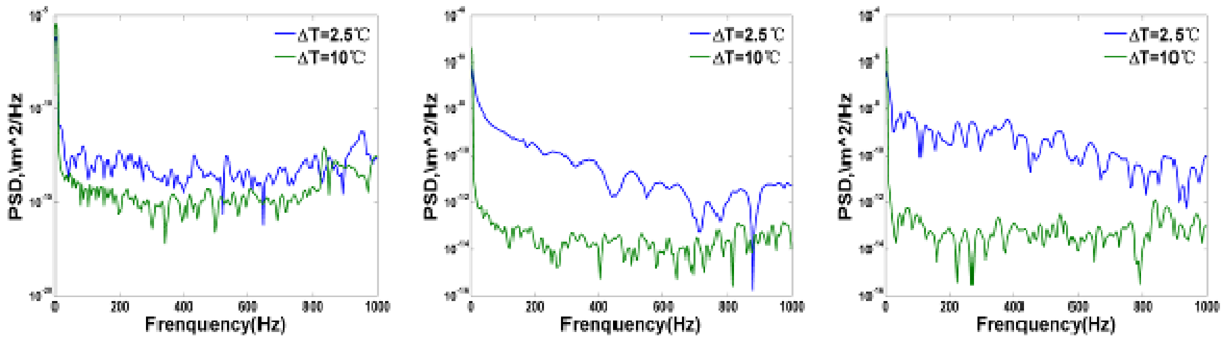


Fig. 4. Random vibration response of a clamped traditional composite plate at SPL=145dB and various temperature rise ΔT .



SPL=140dB SPL=145dB SPL=160dB

Fig. 5. Random vibration response of a clamped traditional composite plate at different SPL and various temperature rises ΔT .

Comparing Fig. 3 with Fig. 4, it can be noticed that with the Sound Pressure Lever increase the thermally buckled equilibrium amplitude and deflection of the plate has a clear snap in the vicinity of critical buckling temperature and tend to be the same slowly with temperature rise. This is mainly because at high temperature the thermal expansion dominates the recovery stress.

Fig. 5 presents the Deflection Power Spectrum Density of a clamped Carbon-Carbon composite panel at different SPL. It can be seen that with the SPL increase the value of Power Spectrum Density (PSD) increase obviously. The deflection PSD plot also shows the domination of the fundamental mode and with the temperature rise the value of PSD increase accordingly. This is demonstrated by the peaks in PSD plots that are broadening and shifting to the higher frequency.

Conclusions

This paper presents a nonlinear finite element model for modeling nonlinear random dynamic behaviors of Carbon-Carbon composite panels under the combined effects of thermal and random acoustic loads. All of the three types of motion 1) linear random vibration about one of the two buckled positions, 2) snap-through motion between the two buckled positions, and 3) nonlinear random vibration over the two thermally buckled positions are be predicted.

It is concluded that the influence of acoustic pressures and temperature to Carbon-Carbon composite material is very obvious. The elevated temperature introduces thermal compression load into the Carbon-Carbon plate, however, the sound pressure has no pronounced effect on the plate, because the acoustic pressure completely dominates the thermal and constrained shape recovery stresses, whereas overlooking these simultaneous actions can affect the accuracy of fatigue life determination.

Results also demonstrated the influences of elevated temperature and random acoustic excitations in controlling the dynamic response along with decreasing the vibration amplitudes. And shifting and broadening the deflection nonlinear random response to the higher frequency in the PSD plots.

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