Research Article

Nonlinear Flutter Response of Heated Curved Composite Panels with Embedded Macrofiber Composite Actuators

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1.Introduction

Since aircraft reached supersonic speeds in the early fifties, a supersonic panel flutter is a well-known phenomenon and many researchers have done intensive theoretical and experimental investigations [1]. The panel flutter is a kind of dynamic aeroelastic instability resulting from the interaction of aerodynamic force, inertial force, and elastic force. For supersonic or hypersonic aircraft, thermal stress induced by aerodynamic heating plays an important role and leads more complex dynamic behaviors.

In the published literature on the panel flutter, a large number of efforts were dedicated to investigate the flat panel flutter in the supersonic or hypersonic flow regime [2–7], while the curvature of the aircraft skin panel exists in the engineering practice of supersonic aircraft structure design. Owing to the inherent curvature, static aerodynamic loading is experienced by a curved panel, and it will result in the static aerodynamic deformation of the curved panel, so the aeroelastic problem of the curved panel will be more complex than that of the flat panel. Dowell [8] had discussed qualitative and quantitative features of the flutter of 2-D and 3-D curved plates in detail without considering the temperature elevation effects, and he showed that the stream-wise curvature reduces the flutter critical dynamic pressure and increases the flutter amplitude, simultaneity.

Azzouz et al. [9–11] had done investigations in static deflection, flutter boundary, and response of curved panels by using the finite element method, and they showed that the flutter response of curved panels is quite similar to the flat panels when the panel’s height rise is very small, and as the panel’s height rises increase the curved panel flutter response reveals a new variety of dynamic behaviors. Ghoman and Azzouz [12,13] studied the nonlinear flutter of curved panels under yawed supersonic flow at elevated temperature by using the frequency-domain method and the
time-domain method, and they showed no critical buckling temperatures are found out for curved panels. Yang et al. [14] proposed a flow field modified local piston theory, which is applied to the integrated analysis on static/dynamic aeroelastic behavior of the curved panel. They showed that the existing curvature modified method is nonconservative compared to the proposed flow field modified method.

How can the panel flutter be suppressed when panel flutter occurs? That is an important subject. Most of the studies on panel flutter suppression mainly rely on smart materials, and piezoelectric materials are the most representative smart materials because piezoelectric materials are capable of altering the structure’s response through sensing, actuation, and control. By now on, the main piezoelectric materials such as piezoceramic [15–17] and MFC [18, 19] are used in panel flutter suppression. Lai et al. [20] studied to control the nonlinear flutter of a simply supported isotropic plate by using piezoelectric actuators. They concluded that the bending moment was effective in flutter suppression. Zhou et al. [21] used the finite element method and LQR full-state feedback to control isotropic and composite panels with surface bonded or embedded piezoelectric patches. The norms of the feedback control gain were used to provide the optimal shape and location of the piezoelectric actuators. Numerical simulations showed that the critical flutter dynamic pressure can be increased up to four times and two times for simply supported and clamped isotropic panels, respectively. Moon [22] employed an optimal control scheme of LQR with output feedback to study the nonlinear flutter suppression of a composite panel with piezoelectric actuators and sensors. The shape and location of the actuators and sensors were determined using the genetic algorithms to obtain maximum control effects. Li et al. [23–25] studied the active aeroelastic flutter suppression of curved composite panels with embedded MFC actuators. Considering the temperature elevation and piezoelectric loads, the constitutive equations for the composite panel with embedded MFC actuators can be represented as

$$\sigma = \left[Q|e_b\right] + \left[Q\right]\left(\varepsilon - [\mathbf{e}]\Delta T - [\mathbf{d}]\varepsilon\right),$$

where $\left[\mathbf{e}_b\right]$ is the total strain vector, $\Delta T$ is the temperature elevation, $[\mathbf{e}]$ is the transformed thermal expansion coefficient vector, $[\mathbf{d}]$ is the transformed piezoelectric constant vector, and $e$ is the electric field.

The electric field with the applied voltage $V$ to the actuator is defined as [24]

$$\begin{bmatrix} e_1 \\ \vdots \\ e_{n_p} \end{bmatrix} = \begin{bmatrix} \frac{1}{h_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{1}{h_{n_p}} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_{n_p} \end{bmatrix},$$

where $h_{n_p}$ indicates the electrode spacing of the interdigitated electrode for the MFC actuator and the subscript $n_p$ means the number of the actuator.
The in-plane forces, bending moments, and the shear forces for the curved composite panels with embedded MFC actuators can be expressed as

\[
\begin{bmatrix}
N \\
M \\
R
\end{bmatrix} = \left[ \begin{bmatrix} A \\ B \\ D \end{bmatrix} \right] \left[ \begin{bmatrix} \epsilon^0 \\ \kappa \end{bmatrix} - \begin{bmatrix} N_{\Delta T} \\ M_{\Delta T} \end{bmatrix} \right] - \left\{ \begin{bmatrix} N_p \\ M_p \end{bmatrix} \right\},
\]

where \( \lambda \) denotes the transverse displacement of the curved panel, \( w_0 \) is the curved panel geometry, and the subscripts, \( x \) and, \( y \) denote the partial differentiation.

In addition, the nondimensional aerodynamic pressure and aerodynamic damping are given as

\[
\lambda = \frac{2 q_a a^4}{\beta D_{11}},
\]

\[
g_a = \frac{\rho_a V_a (M_{\infty}^2 - 2)}{\rho h a^3} = \sqrt{C_a},
\]

\[
D_{11} \text{ is the first entry of the laminate stiffness matrix } [D],
\]

and then,

2.2. The First-Order Piston Theory. The first-order piston theory with the static aerodynamic loading is employed for the aerodynamic pressure load:

\[
p_a = -\frac{2 q_a}{\beta} \left( w_x + \frac{M_{\infty}^2}{M_{\infty}^2 - 1} - \frac{1}{V_a} w_y \right) - \frac{2 q_a}{\beta} w_{0,x} x,
\]

where \( w \) denotes the transverse displacement of the curved panel, \( w_0 \) is the curved panel geometry, and the subscripts, \( x \) and, \( y \) denote the partial differentiation.

In addition, the nondimensional aerodynamic pressure and aerodynamic damping are given as

\[
\lambda = \frac{2 q_a a^4}{\beta D_{11}},
\]

\[
g_a = \frac{\rho_a V_a (M_{\infty}^2 - 2)}{\rho h a^3} = \sqrt{C_a},
\]

\[
D_{11} \text{ is the first entry of the laminate stiffness matrix } [D],
\]

and then,
\[ p_x = -\frac{\lambda D_{11}}{a^3} w_x - \frac{g_x}{\omega_0} D_{11} w_x - \frac{\lambda D_{11}}{a^3} w_{0,x}. \]  

(10)

2.3. Governing Equations. By using the principle of virtual work, the governing equations of the curved composite panels with embedded MFC actuators subject to the combined aerodynamic, thermal, and piezoelectric load can be derived as follows:

\[ \delta W_{\text{int}} - \delta W_{\text{ext}} = 0. \]  

(11)

The virtual work of the internal forces over the curved panel element is given by

\[ \delta W_{\text{int}} = \int_A [\delta e_{\text{el}}]^T [\mathbf{N}] dA + \int_A [\delta e_{\text{th}}]^T [\mathbf{M}] dA \]

\[ + \int_A \alpha_s [\delta e_{\text{p}}]^T [\mathbf{R}] dA, \]  

(12)

where \( \alpha_s \) is the shear correction factor for the laminated composite element.

The virtual work of the external forces over the curved panel element is given by

\[ \delta W_{\text{ext}} = \int_A \delta u^T (-p_h u + p_a) dA + \int_A \delta u^T (-p_h u) dA \]

\[ + \int_A \delta u^T (-p_h v) dA, \]  

(13)

where \( p \) is the density of the panel.

In addition,

\[ \rho h = \frac{1}{\omega_0} \frac{D_{11}}{a^3}. \]  

(14)

Application of the principle of virtual work as shown in equation (11) leads to the equations of motion for nonlinear flutter of curved composite panels with embedded MFC actuators at elevated temperatures and applied voltages, which is expressed as

\[ \frac{1}{\omega_0^2} [\mathbf{M}] [\ddot{\mathbf{W}}] + \frac{g_x}{\omega_0} [\mathbf{G}] [\dot{\mathbf{W}}] + \lambda [\mathbf{A}_x] [\mathbf{W}] \]

\[ + \left( [\mathbf{K}_0] + \alpha_s [\mathbf{K}] - [\mathbf{K}]_T - [\mathbf{K}]_p + [\mathbf{K}]_b \right) [\mathbf{W}] \]

\[ + \frac{1}{3} [\mathbf{N}]_2 [\mathbf{W}] \]

\[ = [\mathbf{P}_T] + [\mathbf{P}_p] - \lambda [\mathbf{P}_{\text{w},x}], \]  

(15)

where the matrix \([\mathbf{M}]\) denotes the system mass matrix; \([\mathbf{G}]\) is the system aerodynamic damping; \([\mathbf{K}_0]\) is the system linear stiffness matrix; \([\mathbf{A}_x]\) is the system aerodynamic stiffness matrix with respect to the \( x \) direction; \([\mathbf{K}]_T\) is the system linear shear stiffness matrix; \([\mathbf{K}]_b\) is the system linear stiffness matrix due to shallow shell geometry; \([\mathbf{N}]_0^s, [\mathbf{N}]_0^h, [\mathbf{N}]_0^N, [\mathbf{N}]_0^N, [\mathbf{N}]_0^N, [\mathbf{N}]_0^N, [\mathbf{N}]_0^N,\) and \([\mathbf{N}]_0^N\) are the system nonlinear first-order stiffness matrices; \([\mathbf{N}]_2\) is the system nonlinear second-order stiffness matrix; \([\mathbf{P}_T]\) is the thermal load; \([\mathbf{P}_p]\)

\[ \text{is the piezoelectric load; and } [\mathbf{P}_{\text{w},x}] \text{ is the static aerodynamic loads causing the static deflection of the panel.} \]

Assuming,

\[ [\mathbf{A}_x] = \lambda [\mathbf{A}_x], \]

\[ [\mathbf{K}_0] = [\mathbf{K}_0] + \alpha_s [\mathbf{K}] - [\mathbf{K}]_T - [\mathbf{K}]_p + [\mathbf{K}]_b, \]

\[ [\mathbf{N}]_1 = [\mathbf{N}]_1^0 + [\mathbf{N}]_1^h + [\mathbf{N}]_1^N + [\mathbf{N}]_1^N + [\mathbf{N}]_1^N, \]

\[ [\mathbf{P}] = [\mathbf{P}_T] + [\mathbf{P}_p] - \lambda [\mathbf{P}_{\text{w},x}], \]  

(16)

the equations of motion for the nonlinear flutter of curved composite panels with embedded MFC actuators can be simplified as

\[ \frac{1}{\omega_0^2} [\mathbf{M}] [\ddot{\mathbf{W}}] + \frac{g_x}{\omega_0} [\mathbf{G}] [\dot{\mathbf{W}}] \]

\[ + \left( [\mathbf{A}_x] + [\mathbf{K}_0] + \frac{1}{2} [\mathbf{N}]_1 + \frac{1}{3} [\mathbf{N}]_2 \right) [\mathbf{W}] = [\mathbf{P}]. \]  

(17)

3. Solution Procedures

The system equations of motion presented in equation (17) are not suitable for numerical integration because of two shortcomings: (1) the number of nodal freedom is too large and (2) the nonlinear stiffness matrices are functions of the system displacement vector. Therefore, to investigate the nonlinear postflutter time response, a straightforward and efficient approach is used to solve directly the system by transferring it into modal coordinates.

Assuming that the panel nodal displacements \([\mathbf{W}]\) can be expressed as a linear combination of selected natural modes and associated modal coordinates,

\[ [\mathbf{W}] = \sum_{r=1}^{n} \Phi_r(t) \phi^{(r)} = [\Phi][\mathbf{a}], \]  

(18)

where \( n \) is the number of the truncation modal.

By substituting equation (18) into equation (17), modal coordinate transformation relations can be introduced:

\[ [\mathbf{M}] = \Phi^T \frac{1}{\omega_0^2} [\mathbf{M}] \Phi, \]

\[ [\mathbf{G}] = \Phi^T \frac{g_x}{\omega_0} [\mathbf{G}] \Phi, \]

\[ [\mathbf{A}_x] = \Phi^T [\mathbf{A}_x] \Phi, \]

\[ [\mathbf{N}]_1 = \Phi^T \sum_{i=1}^{N} a_i [\mathbf{N}]_i \Phi, \]

\[ [\mathbf{N}]_2 = \Phi^T \sum_{i=1}^{N} \sum_{j=1}^{N} a_i a_j [\mathbf{N}]_{ij} \Phi, \]

\[ [\mathbf{K}_0] = \Phi^T [\mathbf{K}_0] \Phi, \]

\[ [\mathbf{P}] = \Phi^T [\mathbf{P}], \]  

(19)
The nonlinear first-order modal stiffness matrices \([N1]_i\) are evaluated with the corresponding linear natural mode \(\Phi_i\). The nonlinear second-order modal matrix \([N2]_i\) is evaluated with a combination of the corresponding linear natural modes \(\Phi_i\) and \(\Phi_j\) simultaneously.

The equations of motion (17) are transformed into the following reduced nonlinear system in the modal coordinate as

\[
[M][\ddot{a}] + [G][\dot{a}] + [K][a] = [P],
\]

where

\[
[K] = [A_0] + \frac{1}{2}[N1] + \frac{1}{3}[N2].
\]

The system of equation (20) can be written in the form of the state-space differential equations as

\[
\begin{bmatrix}
\dot{a} \\
\ddot{a}
\end{bmatrix} = \begin{bmatrix}
0 \\
[I]
\end{bmatrix} \begin{bmatrix}
a \\
\dot{a}
\end{bmatrix} + \begin{bmatrix}
0 \\
0
\end{bmatrix} \begin{bmatrix}
[a] \\
\dot{a}
\end{bmatrix} + \begin{bmatrix}
0 \\
0
\end{bmatrix} \begin{bmatrix}
0 \\
0
\end{bmatrix} \begin{bmatrix}
[a] \\
\dot{a}
\end{bmatrix}.
\]

A fourth-order multimode Runge-Kutta scheme can be used to solve equation (22) for the nonlinear flutter response. Time history, phase portrait, Poincaré map, bifurcation diagram, and Lyapunov exponent are used for better understanding of the pre/postflutter responses of the curved composite panels with embedded MFC actuators.

4. Results and Discussion

In this paper, a clamped curved composite panel with embedded MFC actuators is taken as an example to study the nonlinear flutter response. The lay-up of the curved composite panel is \([0/\theta_{\text{MFC}}/-45/90]_s\). \(\theta_{\text{MFC}}\) indicates the lamination angle of the MFC actuator. The planar dimension of the panel is \(a = 0.381\) m and \(b = 0.305\) m. The material properties for graphite/epoxy and MFC used in this example are shown in Table 1.

Figure 3 depicts the bifurcation diagram versus dynamic pressure for \(H/h = 0.2\) and \(\Delta T/\Delta T_{\text{cr}} = 1\) without applied voltages. Parameters \(H/h\) and \(\Delta T/\Delta T_{\text{cr}}\) are used as the measure of the curvature and temperature elevation, respectively. Unlike the flat panel system, the transverse displacement in the preflutter region shows a gradual static displacement between \(0 \leq \lambda < 410\), which is because of the existence of curvature, and the static aerodynamic loading will be experienced by the curved panel and will result in the static aeroelastic deformation. Figure 4(a) shows the typical time history response and phase maps of the curved panel at \(\lambda = 400\) and the panel converges at a stable equilibrium point \((-0.08, 0)\) finally. With the increasing of dynamic pressure, a Hopf bifurcation happens indicating the flutter onset by a direct jump into limit cycle oscillation at \(\lambda = 410\). The nonlinear flutter response is mainly limit cycle oscillation between \(410 \leq \lambda < 1000\). The typical time history response, phase portrait, and Poincaré map at \(\lambda = 900\) are shown in Figure 4(b), and it is a one periodic limit cycle motion. There are only one maximum value (peak value) and one minimum value (valley value) in one period shown in the time history diagram; a 2-D close loop is shown in the phase diagram and one point is shown in the Poincaré diagram. Between \(1000 \leq \lambda < 1140\), the curved panel will experience quasiperiodic motion; however, the LCO exists in this range. The typical time history response, phase portrait, and Poincaré maps at \(\lambda = 1010\), \(\lambda = 1040\), and \(\lambda = 1100\) are shown in Figures 4(c)–4(e). The quasiperiodic motion is similar as chaotic motion from time history response and phase maps; however, a closed loop cycle is shown in the Poincaré map which indicates a quasiperiodic motion. When \(\lambda \geq 1140\), the curved panel starts to fall in the chaotic motion; Figure 4(f) shows the typical time history response, phase portrait, and Poincaré map of the curved panel at \(\lambda = 1150\) and the largest Lyapunov exponent is 0.1495 which indicates a chaotic motion. Otherwise, in this region, the quasiperiodic motion also exists as shown in Figure 4(g).

Figure 5 shows the bifurcation diagram versus dynamic pressure for \(H/h = 0.2\) and \(\Delta T/\Delta T_{\text{cr}} = 2\) without

| Table 1: Material properties and thicknesses of graphite/epoxy and MFC. |
|-----------------|-----------------|-----------------|
|                 | Graphite/epoxy   | MFC             |
| \(E_1\) (GPa)   | 155             | 30.336          |
| \(E_2\) (GPa)   | 8.07            | 15.857          |
| \(G_{12}\) (GPa)| 4.55            | 6.310           |
| \(G_{23}\) (GPa)| 3.25            | 5.906           |
| \(\nu_{12}\)    | 0.22            | 0.31            |
| \(\nu_{21}\)    | 0.011           | 0.16            |
| \(\alpha_1\) (C\(^{-1}\))| \(-0.07 \times 10^{-6}\) | 4.772 \times 10^{-6}\)|
| \(\alpha_2\) (C\(^{-1}\))| 30.1 \times 10^{-6}\) | 1.555 \times 10^{-5}\) |
| \(d_{11}\) (\times 10^{-12} m\(^{-1}\)) | N/A | 460 (>1000 kV-mm\(^{-1}\)) |
| \(d_{12}\) (\times 10^{-12} m\(^{-1}\)) | N/A | 400 (<1000 kV-mm\(^{-1}\)) |
| \(\rho\) (kgm\(^{-3}\)) | 1586 | 5115.86 |
| Thickness (m)   | 1.5875 \times 10^{-4} | 3.0226 \times 10^{-4} |
| Electrode spacing (m) | N/A | 5.334 \times 10^{-4} |

\(\lambda\) Figure 3: Bifurcation diagram versus dynamic pressure for \(H/h = 0.2\) and \(\Delta T/\Delta T_{\text{cr}} = 1\).
Figure 4: Continued.
applied voltages. Compared to Figure 3, this bifurcation has a big difference which illustrates the effect of the temperature elevation is very strong. It also shows that an aerostatic deflection occurs between the dynamic pressures $0 \leq \lambda < 250$ as shown in Figure 6(a) at $\lambda = 240$. Beyond $\lambda = 250$, it is seen that the chaotic motion occurs and there is no gradual motion transition from static phase to LCO and then to chaotic oscillations; the shift is sudden, and the flutter is onset directly into chaotic motion. Figure 6(b) shows the typical time history response, phase portrait, and Poincaré map of the curved panel at $\lambda = 250$ and the largest Lyapunov exponent is 0.1271. Compared to the stability boundary in the case $\Delta T/\Delta T_{cr} = 1$, the critical dynamic pressure decreases with the increasing of the temperature elevation. When $250 \leq \lambda < 990$, LCOs and quasiperiodic motions all exist in this range as shown in Figure 6(c) at $\lambda = 780$ and Figure 6(d) at $\lambda = 930$. When $\lambda \geq 990$, the curved panel starts to fall in the chaotic motion; Figure 6(e) shows the typical time history response, phase portrait, and Poincaré map of the curved panel at $\lambda = 990$ and the largest Lyapunov exponent is 0.1573. Figure 7 shows the bifurcation diagram versus dynamic pressure for $H/h = 0.2$ and $\Delta T/\Delta T_{cr} = 1$ with the applied voltage $V_U = V_L = 1000$ V. Compared to Figure 3, the bifurcation diagram changes greatly and the response
Figure 5: Bifurcation diagram versus dynamic pressure for $H/h = 0.2$ and $\Delta T/\Delta T_{cr} = 2$.

Figure 6: Continued.
amplitudes of the curved composite panel with embedded MFC actuators are reduced evidently under the applied voltage. An aerostatic deflection is occurred between the dynamic pressures $0 \leq \lambda < 500$ as shown in Figure 8(a) at $\lambda = 490$. With the increasing of dynamic pressure, a Hopf bifurcation happens at $\lambda = 500$, which indicates that the applied voltage will increase the critical aerodynamic pressure. And the nonlinear flutter response is mainly limit cycle oscillation in the range of $500 \leq \lambda < 1190$. Figure 8(b) shows the typical time history response, phase portrait, and Poincaré map of the curved panel at $\lambda = 1000$. The curved composite panel with embedded MFC actuators will experience quasiperiodic motion in the range of $500 \leq \lambda < 1190$ and chaotic motion in the range of $1350 \leq \lambda < 1510$; Figures 8(c) and 8(d) show the typical time history response, phase portrait, and Poincaré maps of the curved panel, respectively. When $\lambda \geq 1510$, the motion of the curved composite panel with embedded MFC actuators will experience LCO motion as shown in Figure 8(e) at $\lambda = 1600$.

5. Conclusion

In this paper, the nonlinear flutter responses of curved composite panels with embedded MFC actuators are studied subject to thermal loading and the applied voltage; some concluding remarks can be drawn:

![Figure 6: Time history, phase portrait, and Poincaré maps under different dynamic pressures. (a) $\lambda = 240$. (b) $\lambda = 250$. (c) $\lambda = 780$. (d) $\lambda = 930$. (e) $\lambda = 990$.](image)
Figure 7: Bifurcation diagram versus dynamic pressure for $H/h = 0.2$, $\Delta T/\Delta T_{cr} = 1$, and $V_u = V_L = 1000$ volts.

Figure 8: Continued.
Unlike the flat panel system, the transverse displacement of the curved composite panel with embedded MFC actuators in the prefutter region shows a gradual static displacement. This is because of the existence of curvature, and the static aerodynamic loading will be experienced by curved panels and will result in the static aeroelastic deformation.

The dynamic behavior of the curved composite panels becomes more complex because of the temperature elevation. The critical dynamic pressure will decrease with the increasing of the temperature elevation, and the system does not evolve chaotic motions through period-doubling bifurcation while the system parameters vary and the chaotic motions occur directly after static motion.

The applied voltage has a great influence to the nonlinear flutter response of the curved composite panel with embedded MFC actuators. It can increase the critical dynamic pressure and change the bifurcation diagram of the curved panel response.

Figure 8: Time history, phase portrait, and Poincaré maps under different dynamic pressures. (a) $\lambda = 490$. (b) $\lambda = 1000$. (c) $\lambda = 1220$. (d) $\lambda = 1480$. (e) $\lambda = 1600$. 

(1) Unlike the flat panel system, the transverse displacement of the curved composite panel with embedded MFC actuators in the prefutter region shows a gradual static displacement. This is because of the existence of curvature, and the static aerodynamic loading will be experienced by curved panels and will result in the static aeroelastic deformation.

(2) The dynamic behavior of the curved composite panels becomes more complex because of the temperature elevation. The critical dynamic pressure will decrease with the increasing of the temperature elevation, and the system does not evolve chaotic motions through period-doubling bifurcation while the system parameters vary and the chaotic motions occur directly after static motion.

(3) The applied voltage has a great influence to the nonlinear flutter response of the curved composite panel with embedded MFC actuators. It can increase the critical dynamic pressure and change the bifurcation diagram of the curved panel response.
Under the in-plane actuation with the applied voltage, the response amplitudes can be reduced evidently. So, the MFC actuator can be used to suppress the panel flutter.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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