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Supersonic flutter of laminated composite panel in coupled multi-fields

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ABSTRACT

The flutter of a laminate composite panel subjected to aerodynamic, thermal, and acoustic load is investigated in the present study. The von-Karman large deflection plate theory is adopted to account for the geometrical nonlinearities. The third order piston theory is employed to estimate the aerodynamic pressure induced by the supersonic airflow. The acoustic excitation is considered to be a stationary white-Gaussian random pressure with zero mean, and the temperature field is assumed to be a constant in the modeling process. Based on the Hamilton principle, the coupled partial differential governing equations of the panel are established and then the assumption mode method is adopted to truncate the governing equations to a set of nonlinear ordinary differential equations, which are then solved by the fourth-order Runge–Kutta numerical integration method. The simulation shows that both the acoustic and thermal loadings have significant effect on the dynamic response of the panel at high acoustic pressure level.

1. Introduction

Panel flutter is a kind of self-excited oscillation of the airfoil resulting from the interaction of the inertial force, elastic force of the panel and the aerodynamic loads when the airfoil is exposed to the supersonic flow. The flutter, which differs from wing flutter only in that the aerodynamic force resulting from the airflow acts only on one side of the panel, may lead potential threat to the safety and life of the panel. The problem of panel flutter has been studied analytically, numerically and experimentally by scholars in the past five decades. A deliberate survey of the early studies was given by Dowell [1]. Later, more and more methods were introduced to obtain the analytical and/or numerical solution of the panel flutter, e.g., the perturbation method [2], the Newmark implicit time integration method [3], the Galerkin method [4], the finite element method [5,6], the finite difference scheme method [7] and the boundary element method [11], all of which were proved to be efficient. Most flutter analyses can be placed in one of four categories based on the structural and aerodynamic theories employed: (1) linear structural theory, quasi-steady aerodynamic theory; (2) linear structural theory, full linearized (inviscid, potential) aerodynamic theory; (3) nonlinear structural theory, quasi-steady aerodynamic theory; and (4) nonlinear structural theory, linearized aerodynamic theory. Analysis of the first type have two major weaknesses: (a) it does not account for structural nonlinearities, hence it can only determine the flutter boundary and can give no information about the flutter amplitudes; and (b) the use of quasi-steady aerodynamics neglects the three dimensionality and unsteadiness of the flow, hence it cannot be used in the transonic region where the flutter is most likely to occur. Analyses of the second type are intended to remedy weakness (b) but this type still has weakness (a); the third type remedies weakness (a), but still posses weakness (b); the fourth type remedies both (a) and (b) [8].

Actually, when the flight Mach number is high ($M > 2$), the aerodynamic heating effect becomes very manifested on account of the fluid/structure interaction. The thermal environment can affect panel motions by introducing thermal in-plane forces and thermal bending moments, and altering material properties [9]. The temperature distribution over the vehicle, and the heat transfer between the skin and the surrounding fluid could also influence the aeroelastic behavior. Lee and Kim [10] investigated the thermal flutter of functionally graded panel based on Newmark time integration method. The temperature through thickness was assumed to be governed by the one-dimensional Fourier equation of heat conduction. Kouchakzadeh [4] studied the flutter of laminate composite plate using the Galerkin method and the direct numerical integration. The effects of fiber orientation, elastic modulus, and mass ratio on the dynamic behavior of the plate were studied.

In addition, the skin of the flight vehicles is subjected to simultaneously high acoustic pressure level induced by the engine and supersonic airstream, which will significant affect the fatigue life of the flight vehicles. Studies on the panel flutter subjected

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Nomenclature

W	dimensionless amplitude of the transverse vibration
u, v, w	displacements in the x, y, z directions, respectively
γ	the ratio of specific heats of the free airstream
SPL	the sound pressure level in decibels
λ_{cr}	critical flutter dynamic pressure
u_0, v_0, w_0	displacements of the mid-plane in the x, y, z directions, respectively
δU	virtual strains energy
$D_{11}^{(0)}$	the value of the mass moment of inertias when all of fibers are aligned with the x axis
α_x, α_y	thermal expansion coefficients in the x and y directions
v_∞	relative free airstream velocity
q	dynamic pressure
υ_{12}	Poisson ratio
E	Young's moduli
S_p	the cross-spectrum density
f_u	the upper cut-off frequency
θ	fiber angle
ΔT_{cr}	critical bulking temperature
p_0	reference pressure
$p(t)$	Gaussian random pressure
A	Jacobian matrix of the zero solution
λ	dimensionless dynamic pressure ($= 2qa^3/MD_{11}^{(0)}$)
a, b, h	panel length, width, thickness, respectively
$\varepsilon_{xT}, \varepsilon_{yT}$	strains induced by thermal effect in the x, y directions, respectively
r	the amount of numbers of the Gaussian random function
e_m	the maximal real part of eigenvalues of the matrix A
δV	virtual work done by aerodynamic and acoustic forces
δT	virtual kinetic energy
I_0, I_1, I_2	normal, coupled normal rotary and rotary inertia coefficients, respectively
PW	the power of the Gaussian random pressure
i, j	mode number
Δp	aerodynamic pressure
ρ_a	relative free airstream density
ρ_0	panel density
$\bar{Q}$	lamina stiffness matrix
S_0	a constant of the cross-spectrum density
N_{kl}, M_{kl}	the force resultants operators
μ	mass ratio
M	Mach number
$T_0, T_1, \Delta T$	initial temperature, current temperature and temperature difference, respectively

to acoustic load have received increasing attention in recent years [11]. The acoustic excitation was usually considered to be a stationary white-Gaussian random pressure with zero mean in the existing literature. Kitipornchai [12] studied the random vibration of functionally graded laminates panel with random variations in system variables. They found that the effect of the volume fraction index on the variation in natural frequencies was important when individual material property was taken as the random input variable. Ibrahim et al. [8,13] studied the flutter of FGM (functionally graded material) panel subjected to acoustic and thermal loads and presented the time-domain solution of clamped FGM panel. The results showed that the FGM panels were not always superior in the performance compared to the metal panels at different temperatures. Motagaly et al. [14] gave the response of nonlinear panels subjected to combined acoustic and aerodynamic pressures using finite element method. The simulation indicated that the acoustic pressure should be considered for $\lambda > \lambda_{cr}$. Ng [15] studied the nonlinear acoustic response of thermally buckled plates using single model. The results showed that the simple analysis procedure using single mode representation of displacement can predict the general trends of the dynamic behavior of thermally buckled plates.

Due to the particular property of lightening the weight of structures, composite materials have been more and more applied in the design of flight vehicles. The present paper is an exploratory study to reveal the flutter of laminate composite panel flutter subjected to aerodynamic, thermal, and acoustic excitation based on the third order piston theory. In what follows, the von-Karman large deflection plate theory and the third-order piston theory are applied to establish the partial differential governing equations of the panel. The panel is assumed to be exposed to the airflow at a constant speed for a sufficient time so that the temperature field is a constant through the panel area. The acoustic excitation is considered to be a stationary white-Gaussian random pressure with zero mean. The assumption mode method and the Runge–Kutta method are employed to simulate the dynamic responses of the system. The effects of fiber orientation, temperature, acoustic level, and the order of piston theory on the system behavior are discussed in detail, respectively.

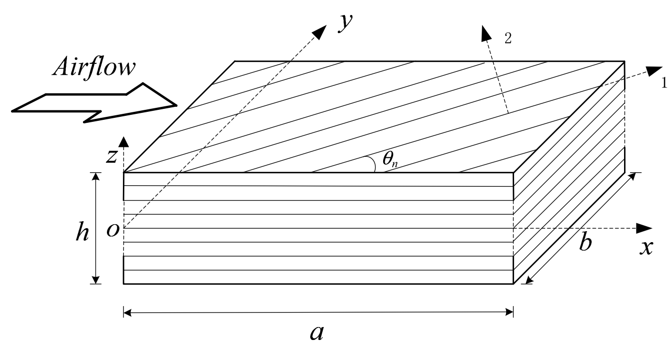

Fig. 1. The sketch of the panel geometry.

2. Aerodynamic modeling

Consider a laminated composite panel with length a, width b, and thickness h as shown in Fig. 1. The panel composed of 8 layers is subjected to the supersonic flow in the positive x direction. The origin of the fixed coordinate system o-xyz is located at the panel corner on the mid-plane. According to the Kirchhoff hypothesis, the transverse displacement, w, is independent of the transverse coordinate, z, the transverse normal and shear strains are zero, and the displacements $u(x, y, z, t)$, $v(x, y, z, t)$ and $w(x, y, z, t)$ of any point of the panel are assumed to be functions of the displacements of the mid-plane. Hence, the displacements can be expressed as

$$\left.\begin{aligned} u(x,y,z,t) &= u_0(x,y,t) - z\partial_x w_0(x,y,t), \\ v(x,y,z,t) &= v_0(x,y,t) - z\partial_y w_0(x,y,t), \\ w(x,y,z,t) &= w_0(x,y,t), \end{aligned}\right\} \tag{1}$$

where u_0, v_0 and w_0 are the displacements of the mid-plane in the x, y and z directions, respectively. '∂' denotes the derivative with respect to coordinate. It is assumed that the panel is exposed