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Aeroelastic stability analysis of heated flexible panel subjected to an oblique shock

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Abstract The critical conditions for aeroelastic stability and the stability boundaries of a flexible two-dimensional heated panel subjected to an impinging oblique shock are considered using theoretical analysis and numerical computations, respectively. The von-Karman large deflection theory of isotropic flat plates is used to account for the geometrical nonlinearity of the heated panel, and local first-order piston theory is employed in the region before and after shock waves to estimate the aerodynamic pressure. The coupled partial differential governing equations, according to the Hamilton principle, are established with thermal effect based on quasi-steady thermal stress theory. The Galerkin discrete method is employed to truncate the partial differential equations into a set of ordinary differential equations, which are then solved by the fourth-order Runge-Kutta numerical integration method. Lyapunov indirect method is applied to evaluate the stability of the heated panel. The results show that a new aeroelastic instability (distinct from regular panel flutter) arises from the complex interaction of the incident and reflected wave system with the panel flexural modes and thermal loads. What's more, stability of the panel is reduced in the presence of the oblique shock. In other words, the heated panel becomes aeroelastically unstable at relatively small flight aerodynamic pressure.

1. Introduction

Panel flutter is a phenomenon of self-excited oscillation which may occur from the interaction of the inertial force, elastic force and the aerodynamic loads induced by the supersonic flow. This self-excited oscillation may cause fatigue of the panel or supporting structure, functional failure of equipment attached to the structure, or excessive noise levels in space vehicle compartments near the fluttering panel.[1] This phenomenon was first observed by Jordan[2] who suggested that a lot of early V-2 rocket failures might have resulted from panel flutter. However, formal studies have been carried out based on different structural and aerodynamic theories since the 1950 s. Excellent reviews have been provided by Dowell[3] and Mei et al.[4] The early studies on the panel flutter are based on linear theory, and the critical flutter velocity is provided.

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Nomenclature

a	speed of sound
a_∞	free stream sound velocity
D	plate stiffness
E	modulus of elasticity
h	plate thickness
l	plate length
Ma	Mach number
N	mode number
N_x	in-plane force
$N_x^{(\mathrm{T})}$	applied in-plane thermal stress
p	aerodynamic pressure
$q=\rho_\infty U_\infty^2/2$	dynamic pressure
R_x	non-dimensional in-plane force
$R_x^{(\mathrm{T})}$	non-dimensional applied in-plane thermal stress
t	physical time
T_0	initial temperature of the panel
w	plate deflection
W	non-dimensional plate deflection
x	streamwise coordinate
α	coefficient of thermal expansion

$\beta=\sqrt{Ma^2-1}$	Prandtl-Glauert factor
γ	air specific heat ratio
ΔT	temperature change
λ	non-dimensional dynamic pressure
υ	Poisson's ratio
ρ	density of plate
$\rho_\infty, U_\infty, p_\infty, Ma_\infty$	free stream air density, velocity, pressure, Mach number
τ	non-dimensional time
σ	shock angle

Subscripts

u	upper surface of the panel
d	lower surface of the panel
l	left side of the shock
m	middle part of the shock
r	right side of the shock
loc	local condition

When the velocity of flow is above the value, the motion amplitude of the panel increases exponentially with time. Hedgepeth[5] and Dugundji[6] studied the problem of panel flutter based on the linear theory. However, the motion of the panel is generally restrained to a bounded limit cycle because of structural nonlinearities. The linear theory can only determine the critical dynamic pressure, frequency of vibration and mode shape during the instability, and give no information about the panel deflection and stress.[7] Hence, the nonlinear structure theory should be employed in the analysis of the panel flutter[8] and von Karman plate theory[9] has been widely adopted to introduce geometrical nonlinearity.

Potential flow theories aimed at providing predictions of the unsteady aerodynamics have been given by Dowell.[10,11] Vedeneev[12] has considered a two-dimensional panel flutter problem using potential gas flow theory. However, the exact potential flow theory is not widely used for the unsteady aerodynamics modeling because of its greater complexity compared to piston theory. Many researchers have employed the piston theory in the analysis of panel flutter since the theory was developed by Lighthill[13] and Ashley et al.[14] The "piston theory" is a method for calculating the aerodynamic loads on aircraft in which the load pressure generated by the body's motion is related to the local normal component of fluid velocity in the same way that these quantities are related at the face of a piston moving in a one-dimensional channel. In 1966, Dowell adopted the von-Karman plate theory and the first-order piston theory to study panel flutter of two- and three-dimensional plates and the case has become a classical one in panel flutter studies. Lee et al.[15] used the first-order piston theory to model aerodynamic loads, and the Newton-Raphson iteration method and complex eigenvalue solver with the Linearized Updated Mode/Nonlinear Time Function (LUM/NTF) approximation method approximation method to obtain the postbuckled deflection and flutter information, respectively. Koo and Hwang[16] applied the finite element method to study the effects of distributed structural damping on the flutter boundaries of composite plates with the linear piston theory used to compute the unsteady aerodynamic load in a supersonic flow. Zhao and Cao[17] employed the third-order piston theory to estimate the nonlinear aerodynamic pressure induced by the supersonic airflow in numerical analysis of the flutter of a stiffened laminate composite panel. Some other principal publications based on piston theory are mentioned by Bolotin[18], Dowell[19] and Algazin and Kiiko.[20] Euler equations[21,22] and Navier-Stokes equations[23–26] are also used in analysis of panel flutter for calculating the unsteady aerodynamics. Recent experimental[27] and numerical[28] investigations for single-degree-of-freedom flutter in the transonic flow regime have been performed by Vedeneev et al.

Aerodynamic heating should be considered in the flutter design when the aircraft flies at high Mach number. Temperature increase due to aerodynamic heating or restrained thermal expansion may result in thermal buckling. In general, two simplifying assumptions are used because of the complexity of aerothermoelasticity coupling equations[29,30]: (A) structural deformation has no effect on the temperature field; (B) response time of the panel flutter is much smaller than that of temperature change. In 1958, Houbolt[31] first studied the flutter boundaries and buckling instability characteristics of a two-dimensional plate based on the simplifying assumption of uniform temperature field. Yang and Han[32] employed the finite element method to study the thermal buckling flutter problem of a two-dimensional plate using the same assumption of a uniform temperature field. Xue and Mei[33,34] performed finite element analysis of nonlinear flutter response of isotropic two- and three-dimensional plates with arbitrary shapes.

Most of the existing researches focus on classical panel flutter problem when only one surface of the panel is exposed to supersonic flow and no shock is considered. However, in some

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