Journal of Sound and Vibration 409 (2017) 306–317

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Nonlinear viscoelastic heated panel flutter with aerodynamic loading exerted on both surfaces

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ARTICLE INFO

Article history:
Received 6 December 2016
Received in revised form
5 June 2017
Accepted 19 July 2017

Keywords:
Nonlinear panel flutter
Viscoelastic panel
Aerothermoelastic stability
Bifurcation diagram

ABSTRACT

A nonlinear flutter analysis of viscoelastic heated panels with aerodynamic loading exerting on its both surfaces is presented. The aeroelastic motion equations of such panels can be formulated by using the von Karman large deflection plate theory and piston aerodynamics theory, while the thermal induced membrane force and the Kelvin type viscoelastic damping are taken into account. By using Galerkin method, the continuous partial differential motion equation can be transformed into a set of nonlinear ordinary differential equations with coupled aerodynamic stiffness and aerodynamic/viscoelastic damping terms. By applying Routh-Hurwits criterion, the static divergence stability (buckling) boundary and the elastic/viscoelastic flutter stability boundaries of the panel initial flat equilibrium can be obtained. The obtained linear stability results revealed that the system dynamic bifurcation boundary can be significantly affected by the additive structural viscoelastic damping, and such effect can be enhanced by increasing the dynamic pressure of the external flow exerting on either single panel surface. Additionally, the sum of dynamic pressures exerting on both panel surfaces functions as the dynamic pressure exerting on either single pane surface. The corresponding nonlinear viscoelastic response can be simulated by using the fourth order Runge-Kutta numerical integration method, thus the system bifurcation diagrams with varying dynamic pressures can be obtained. The results revealed that the additive viscoelastic damping may exhibit the paradoxical effect on the system dynamic stability with lower temperature elevation, while the post flutter chaotic motions can be regulated as periodic motions with reduced amplitudes. However, with a higher temperature elevation, the effect of the additive viscoelastic damping can be always stabilizing to both the aeroelastic system stability and the post flutter chaotic motions.

1. Introduction

Panel flutter is a form of aeroelastic instability resulting from the interaction among the deflections of high speed vehicle skin panels, structural inertia force and the potential flow [1]. As the linear panel flutter analysis may predict an unstable motion with exponential growing amplitudes in time scale, the nonlinear panel flutter analysis can predict limit cycle oscillations (LCOs) bounded by the reality boundary conditions and the nonlinear stiffness (considering additive nonlinear stiffness due to large defections, or nonlinear aerodynamic pressures). And the post flutter oscillations can cause severe

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http://dx.doi.org/10.1016/j.jsv.2017.07.033

fatigue damage to the panel structures [2]. Much worse situation is that the panel can be immersed in the thermal radiation environment, thus the thermal induced membrane force can weaken the panel bending stiffness, and can finally result in static instability (buckling), thus make the panel prone to lose aeroelastic stability (panel flutter) [3].

Among the existed studies on panel flutter, Dugundji [4], Dowell [5–7] and Fung [8] et al. [9–13] have developed different flutter analysis methods (including theoretical and experimental methods) to investigate the panel flutter behavior. These studies mainly dealt with the effects of some important system control parameters, such as, in-panel load (mainly induced by the thermal radiation), boundary conditions, flow velocity and static pressure (cavity effect) etc. on the flutter stability and post flutter motions. As for the influence caused by other parameters, L.K. Abbas et al. have conducted a parametric study on supersonic/hypersonic nonlinear flutter behavior of geometrically imperfect curved skin panel, including static/dynamic edge movability, Kelvin type damping model, and nonlinear aerodynamic loading. The significant destabilizing influence of thermal induced degradation of the structural elastic modulus can be investigated, as well as the edge support degradation [14,15]. Most above studies focused on a fluttering panel with its single up surface exposed to the aerodynamic loading. However, in some specific engineering realities, both the up and the bottom surface of the panel like structures in some vehicle frame components, such as engine inlet/nozzle of high-speed flight vehicles, may expose itself to aerodynamic loading exerting on both surfaces with different flow parameters (e.g. dynamic pressures). J. Zhou has investigated the aeroelastic stability of such type heated panels, the results mainly revealed that only if the sum of the aerodynamic pressures on both surfaces satisfies the flutter stability condition, can the panel lose aeroelastic stability [16].

Additionally, similar to the hydro-elastic instability problems, the panel flutter can also be treated as an instability problem of a non-conservative self-excited mechanical system [17,18]. And it is well known that the structural damping can play an important role in the non-conservative system [7,19]. Based on a double mathematical pendulum with a free end subjected to a follower (tangential) force, Ziegler found that the addition of a small amount of damping can reduce the value of the critical force comparing with the value found without considering the damping [20]. CH. Ellen also investigated the influence of structural damping of various types on the panel flutter based on a two-dimensional membrane model. From the perspective of energy conservation law, various kinds of damping are divided into two types, dissipative type and non-dissipative type. Whether the damping, described as $g\left(\partial^{n+1}w/\partial t\partial z^{n}\right)$, is stabilizing or destabilizing depends on its spatial derivation character. On this issue, Dowell also figured out that the paradoxical effect of the damping model may be related to its modal distribution characteristics [6,7]. Without spatial derivation ($n = 0$), the internal structural and the external aerodynamic damping have the same effect, i.e. stabilizing the dynamic behavior, and this type of damping can be described as $g = 2\xi_i\omega_j/\omega_0$, where g is the damping coefficient, ξ_i is the modal damping ratio of the j th mode whose circular frequency is ω_j, and ω_0 is a suitable reference frequency. This kind damping model can always dissipate a quantity of energy per cycle which is proportional to the frequency of the oscillation, and this damping model has always been used to model the elastic structures [21]. Based on a Beck's column model, Y. Sugiyama presented a theoretical method to explain the physical mechanism of the damping destabilizing effect from the perspective of energy. The results revealed that its influence depends on flutter frequency, phase angle, and vibration amplitude, and the gradient of the phase angle was found to be the 'valve', which control how much work the follower forces (non-conservative) can do on the structure during each period of oscillation [22]. Additionally, as polymer matrix composites have become the main structural materials of choice, because of their light weight and relatively high failure stresses. For these materials, even though their initial dynamic behavior may be elastic, to obtain an accurate response prediction with elevated temperatures requires its viscoelastic analysis [23]. Considering the structural hysteresis loops appear experimentally to be frequency independent, thus the damping model should consider the spatial derivation ($n \neq 0$), which may be destabilizing to the non-conservative system, such as panel flutter [19]. It has been experimentally investigated that the Kelvin-Voigt type model, consisting of a Newtonian damper and a Hookean elastic spring connected in parallel, can describe better the observed mechanical and thermo-mechanical response of polycrystalline materials, especially the creep effect at high temperature can be taken into consideration [24].

As noted by the above discussion, there exists a necessary to investigate the combination effect of the viscoelastic damping, aerodynamic pressures and temperature elevations on the aeroelastic stability and the nonlinear response of such viscoelastic panels. Motivated by such reality consideration, the stability and post flutter behaviors of viscoelastic panels with aerodynamic loading exerting on both surfaces are presented in this paper. Based on von Karman geometric nonlinear panel theory, piston aerodynamics theory and Kelvin type viscoelastic damping model, the panel motion equation is derived. And by using Galerkin method, the continuous equation is reduced into a set of nonlinear ordinary differential equations. The static divergence instability (buckling) and the flutter instability of the initial flat panel with elastic/viscoelastic damping are analyzed by using Routh-Hurwits criterion. And the system response is simulated by the fourth order Runge-Kutta integration algorithm. Then by conducting a parametric study including three non-dimensional parameters, temperature elevations, the flow dynamic pressures and the viscoelastic damping coefficient, the system stability and the bifurcation diagram are investigated.

2. Formulation for the equation of motion

In this study, a two-dimensional simply supported heated panel is adopted, as shown in Fig. 1, both its up surface and the bottom surface are simultaneously exposed to airflow.