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Aero-thermo-elastic flutter analysis of coupled plate structures in supersonic flow with general boundary conditions

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A B S T R A C T

The coupled plates are commonly seen in flight vehicle structures, which are always subjected to a severe combination of thermal, aerodynamic and mechanical loads during the cruise. In this paper, a unified solution is derived for the aero-thermo-elastic flutter problems of the coupled plate structure with general boundary conditions, in which the classical and elastic boundary conditions can be dealt with. The Mindlin plate theory in conjunction with the supersonic piston theory to consider the supersonic flow effect is adopted to formulate the theoretical model of the heated coupled plate structure subjected to supersonic flow. Each displacement component of the coupled plate is constructed as a two-dimensional Fourier series supplemented with auxiliary functions in order to satisfy the possible boundary conditions. The flutter analysis of a single flat plate, to which great efforts have been devoted, can be considered as a special case in the proposed model by setting the coupling angle of the coupled plate equal to zero. A considerable number of numerical cases are presented to show the accuracy and efficiency of the proposed method. The effects of the aerodynamic pressure, boundary condition, coupling spring and temperature change on the flutter characteristics of the coupled plate are also discussed in detail. The present formulation permits to analyze the flutter problems of the coupled plate having arbitrary coupling angles and boundary conditions.

1. Introduction

With the increasing use of rectangular composite plates in aerospace and aeronautics engineering applications, the flutter behaviors of these structures in airflow have been substantially investigated by researchers recently. It is well known that flutter is a self-excited oscillation resulting from the elastic force, inertial force and aerodynamic pressure. If the flutter characteristics of the plate with high speed can be identified, then the designers and engineers can optimize these structures to avoid the dangerous dynamic behaviors. Thus, considerable efforts have been devoted to investigating the flutter behaviors of the plate with aerodynamic pressure.

A considerable number of computational methods have been developed to predict the aerodynamic characteristics of plates. Although several special cases [1,2] can be solved by the exact method, approximate methods may be preferred due to

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their wider applicability to the complex structures. Dowell [3–5] adopted the Galerkin's method to investigate the aero-elastic stability characteristics of the plate at supersonic speed. It is noted that at least six orders of modes should be employed to obtain the convergent solutions. Navazi and Haddadpour [6] used the Galerkin's method combined with the Runge–Kutta numerical algorithm to study the aero-thermo-elastic flutter of the functionally graded plate. Li et al. [7] employed the Galerkin's method to investigate the flutter problems of the plate in supersonic flow with the aerodynamic heating considered. Shitov and Vedeneev [8] adopted the Galerkin's method to research the flutter behaviors of a simply supported plate in low supersonic flow. Wang et al. [9] studied the flutter problems of the viscoelastic heated plate with aerodynamic pressure exerted on its both surface by using the Galerkin's method. Meanwhile, the effect of the additive viscoelastic damping was also discussed in detail. Song and Li [10] presented the vibration and aero-elastic flutter analysis of a two-span plate in supersonic flow based on the Galerkin's method, which can serve as a benchmark solution for the multi-span plate structures. Alder [11] proposed a fluid-structure coupling model for the flutter analysis of the plate in transonic flow and the Galerkin's method was employed to obtain the structural deformations. Subsequently, he also studied the dynamic behaviors of the prestressed plate in low supersonic turbulent flow [12]. Shiau and Lu [13] discussed the effects of the fiber orientation and elastic modulus ratio on the flutter behaviors of a two-dimensional simply supported composite laminated plate by using the Galerkin's method. Vedeneev [14] and Yang et al. [15] also employed the Galerkin's method to analyze the influence of the damping on the flutter performances of a two-dimensional plate and a composite plate with viscoelastic mid-layer, respectively. Guo and Mei [16] introduced the aero-elastic modes to investigate the flutter problems of the plate in supersonic flow, which can improve the computing efficiency by reducing the number of nonlinear governing equations. Li and Narita [17] optimized the maximum critical aerodynamic pressure of the plate at supersonic speed based on the layerwise optimization approach. Bondarev and Vedeneev [18] adopted the closed form, numerical and semi-analytical methods to study the instability problems of the plate in supersonic flow with boundary layer effect considered. The assumed mode method (AMM) in conjunction with Ritz method also has been widely used to carry out the flutter analysis of plates and quite a few corresponding publications can be found. The aero-elastic and aero-thermo-elastic flutter analyses of composite laminated plates exposed to supersonic flow were performed and the corresponding control strategies were proposed by Song and Li [19,20]. Meanwhile, investigations on the flutter of the plate at supersonic speed with classical and elastic boundary conditions were also carried out [21]. It is worth highlighting that, although the AMM has promoted abundant literature on the flutter analysis of the plate with high speed, the obtained solutions may be unreliable for the cases with S-C-S-C, S-F-S-F and elastic boundary conditions [21].

As is known to all, the finite element method (FEM) is also a powerful computational method which has been widely used to analyze the flutter behaviors of the plate. The flutter problems of the two-dimensional plates [22–25], isotropic plates [26], composite plates [27,28], stiffened plates [29,30], functionally graded plates [31,32], curved plates [33–35] and multibay plates [36] with high speeds were substantially studied based on the FEM. Koo and Hwang [37] and Singha and Ganapathi [38] employed the FEM to analyze the effects of the aerodynamic parameters on the flutter properties of the plate structures. Cheng and Mei [39] presented a finite element time-domain model for the flutter analysis of the plate exposed to hypersonic flow. Since the errors will be produced by the AMM in calculating the critical aerodynamic pressure of the plate in supersonic flow with some boundary conditions, Song and Li [21] also studied these numerical cases by using the FEM.

The coupled panel structures are widely used in the flight vehicles' design because of their favorable strength-to-weight and stiffness-to-weight ratios. These structures can be modeled as several plates connected together along their connections with specific angles. Three types of waves (longitudinal, shear and bending waves) can be transformed into each other due to the wave reflection and refraction at these junctions [40], which makes the dynamic analysis of the coupled plate structure very complicated.

A vast amount of information is available on the dynamic analysis of the coupled plate structure. In the low-frequency range, the FEM has been widely adopted to the structural analysis of the coupled plate. Hambric [41] used the FEM to analyze the power flow and mechanical intensity of a simple truss and a beam-stiffened cantilever plate. Mace and Shorter [42] employed the FEM to investigate the dynamic characteristics of the three coupled plates. Grice and Pinnington [43] proposed a finite element model to analyze the vibration properties of a thin-plate box structure. Besides, the energy-based approaches, such as the power flow analysis (PFA) and statistical energy analysis (SEA) are mostly utilized for the mid-frequency and high-frequency analyses of the coupled plate structures, respectively. Cuschieri [44] and Cuschieri and McCollum [45] used the PFA to research the vibration and wave transmission characteristics of an L-shaped plate. Similarly, a large number of studies concerning the vibration behaviors of the coupled plate by using the SEA have been found [46–48]. Although the FEM, PFA and SEA can be employed to obtain reasonably accurate solutions for the dynamic problems of coupled plate structures, the disadvantage is that the computational process is quite time consuming and these methods may be inefficient to carry out the parametric analysis.

The dynamic stiffness method (DSM), as another effective computational method, has been widely adopted to evaluate the vibration problems of the coupled plate. Langley [49], Bercin [50,51], Farag and Pan [52], Kessissoglou [53], Li et al. [40] and Wu et al. [54] used this method to investigate dynamic characteristics of coupled plate structures. Although the DSM is an efficient analytical approach and can be readily used to reveal the mechanism of the structures, it can be found that the computational cases in the aforementioned publications are confined to the coupled plates having at least two opposite edges simply supported. Recently, Li [55,56] proposed a modified Fourier method for the vibration analysis of beams and plates with arbitrary boundary conditions. The modified Fourier method has attracted considerable research interest and has been further extended to study the vibration behaviors of the coupled plate structures with arbitrary boundary conditions [57–61].