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Aero-hygrothermal effects on stability regions for functionally graded panels

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ABSTRACT

This paper presents the aero-hygrothermal stability and nonlinear flutter behaviors of functionally graded panels. In this regard, the elastic, thermal and moisture expansion coefficients of the model vary continuously through the thickness directions in the volume fractions. For more effective evaluations of the material properties, Mori–Tanaka scheme is employed with respect to power-law (P-) and sigmoid (S-) models. Applying the principle of virtual work, governing equations of motion are derived. To check the validity of present works, results are compared with previous data. Especially, the aero-hygrothermal stability regions are compared based on the P- and S-FGMs for various ranges of the temperature, moisture and volume fraction index. Finally, the nonlinear dynamic behaviors of the models are investigated using Newmark time integration method in the stability regions.

1. Introduction

Modern flight structures are frequently experienced moist and thermal environments during operating life. Generally, the correlation of moisture and temperature are so called hygrothermal conditions, and then the strength and stiffness of the structure can be reduced due to the induced residual stresses and extensional strains. Humidity, water, high temperature and aerodynamic loading may also induce special static and dynamic behaviors such as instability and catastrophic failure. Therefore, the design of the structure requires special attention to the variations of temperature and humidity.

The research works on the hygrothermal effects have been studied earlier for laminated composite model. Whitney and Ashton [1] presented the theoretical analysis of the effects on the static and vibration of lamina plates using the Ritz method. Ram and Sinha [2] investigated the bending and free vibration behaviors of the model using the finite element method. Chao and Shyu [3] also obtained the buckling loads for composite models under temperature and moisture loading. Additionally, Bahrami and Nosier [4] employed the displacement fields of laminates under thermal and hygroscopic loadings, and studied the predicting the inter-laminar stress distributions. Besides, Lo et al. [5] dealt with the concentration effects of the temperature and moisture of the model. Recently, Natarajan et al. [6] investigated the effect of moisture concentration and the thermal gradient on the free vibration and buckling of composite plates.

In the past few decades, new advanced materials have been proposed to enhance the performance of structures. Then, the concepts and applications of functionally graded materials (FGMs) are developed in the work [7]. Conventional composite materials may have delamination and adhesive bond separation due to mismatch the properties between the layers. In this regard, many engineers have studied the characteristics and applications of FGM structures. Ferreira et al. [8] performed the static deformations of the plate by using the robust meshless method and a higher-order shear deformation theory. Nosier and Fallah [9] studied the nonlinear analysis of circular plates under asymmetric transverse mechanical loading. Also, Lee and Kim [10] performed thermal postbuckling behavior and snap-through characteristics of the three types of FG panels in hypersonic flow. Furthermore, Wattanasakulpong et al. [11] fabricated layered FG beam by the sequential infiltration technique, and then obtained results on free vibration. Kumar et al. [12] also developed FG composite models, and then investigated experimental results of thermo-mechanical behaviors.

On the other hand, one of the significant applications of FGMs is the skin of aerospace vehicles such as panel flutter and stability boundaries. Prakash and Ganapathi [13] studied the supersonic flutter of plate model subjected to aerodynamic pressure.

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Ibrahim et al. [14] investigated nonlinear flutter and thermal buckling of panels based on first-order shear deformation theory. Navazi and Haddadpour [15] presented analytical research on aero-thermoelastic stability boundaries using the piston theory. Also, Lee and Kim [16] studied the stability and flutter behaviors for P-, S- and E-FGMs. While, active aeroelastic control of the plates using piezoelectric actuator and sensor have been investigated to suppress the nonlinear flutter behavior [17,18]. Further, a few research works have been performed static behaviors of FGM in the hygrothermal environments. Zenkour [19] dealt with the static analysis of FGM plate resting on elastic foundations using the sinusoidal plate theory. Additionally, Lee and Kim [20,21] analyzed hygrothermal characteristics of FGM model in detail. Recently, Saadatfar and Khafri [22] studied hygrothermal loading, elastic foundation and electromagnetic conditions on the static behavior of the FG magneto-electro-elastic hollow sphere.

In this study, stability regions of the P- and S-FGM models are studied under hygrothermal and aerodynamic environments. For the structural models, the first-order shear deformation theory of plate is used, and von Karman strain–displacement relations are employed. On the other hand, first-order piston theory is applied to consider the airflows. Finally, stability boundaries are investigated for various ranges of temperature, moisture and volume fraction index. Furthermore, the aero-hygrothermal behaviors of the models are discussed in the stability regions.

2. Formulations

Functionally graded materials (FGMs) are made of continuously gradient heterogeneous materials for application to the environmental situations. Generally, FGM models are made as ceramic on the top and metal at the bottom parts, respectively. Also, the length, width and thickness of the model are a, b and h, respectively [10].

2.1. Effective material properties

In this work, two types of models are chosen as the power-law FGM (P-FGM) and the sigmoid FGM (S-FGM).

At first, a simple power law function is considered to represent the ceramic volume fraction V_c as

$$V_c(z) = \left(\frac{z}{h} + \frac{1}{2}\right)^k \quad (0 \le k < \infty) \tag{1}$$

Next, a sigmoid function is used to reduce the stress concentrations in a single power-law portion. Then, the ceramic volume fraction can be obtained as

$$\begin{aligned} V_{c1}(z) &= 1 - \frac{1}{2}\left(1 - \frac{2z}{h}\right)^k \quad (0 \le z \le h/2) \\ V_{c2}(z) &= \frac{1}{2}\left(1 + \frac{2z}{h}\right)^k \quad (-h/2 \le z \le 0) \end{aligned} \tag{2}$$

where k is the volume fraction index.

In the conventional modeling of FGMs, rule of mixture has been most frequently used to express the effective properties due to the simplicity of expression and estimation. However, the method cannot evaluate the interaction among adjacent inclusions. In this regard, the Mori–Tanaka homogenization method is used for estimating the material properties of the graded microstructure. Based on the homogenization scheme, the effective elastic modulus E and Poisson's ratio ν of the structure can be obtained as [23]

$$E(z,T) = \frac{9K(z,T)G(z,T)}{3K(z,T) + G(z,T)}, \quad \nu(z,T) = \frac{3K(z,T) - 2G(z,T)}{6K(z,T) + 2G(z,T)} \tag{3}$$

where K and G are the bulk and shear modulus of the model, and can be expressed as

$$\begin{aligned} K(z,T) &= K_m(T) + \frac{V_c(z)(K_c(T) - K_m(T))}{1 + (1 - V_c(z))\dfrac{3K_c(T) - 3K_m(T)}{3K_m(T) + 4G_m(T)}} \\ G(z,T) &= G_m(T) + \frac{V_c(z)(G_c(T) - G_m(T))}{1 + (1 - V_c(z))\dfrac{G_c(T) - G_m(T)}{G_m(T) + f_1(T)}} \\ f_1(T) &= \frac{G_m(T)(9K_m(T) + 8G_m(T))}{6K_m(T) + 12G_m(T))} \end{aligned} \tag{4}$$

where V, subscripts c and m represent the volume fraction, ceramic and metal, respectively. Furthermore, the volume fractions of the models follow the relationship of $V_c + V_m = 1$, and mass density ρ is evaluated using the rule of mixture as $\rho = \rho_m V_m + \rho_c V_c$.

Then, the distributions of the ceramic volume fraction V_c according to the indices k are presented in Fig. 1. Overall, the distributions of the S-FGM case are composed of two P-FGM types. The amount of metal is richer than ceramic as the indices k increase in P-FGM type, while S-FGM model shows equal quantities of constituent materials with different indices k. In other words, total amounts of ceramics and metals are same regardless of index k in S-FGM case, and thus the results according the variations of the index k are almost the same in comparison with the P-FGM model.

2.2. Stress and strain relations

The displacement fields (u, v, w) are based on the first-order shear deformation theory of model. At a point (x, y, z), plates are expressed as functions of mid-plane displacements (u_0, v_0, w_0), and ϕ_x and ϕ_y are the rotation of originally perpendicular to the longitudinal plane.

$$\begin{aligned} u(x,y,z,t) &= u_0(x,y,t) + z\phi_x(x,y,t) \\ v(x,y,z,t) &= v_0(x,y,t) + z\phi_y(x,y,t) \\ w(x,y,z,t) &= w_0(x,y,t) \end{aligned} \tag{5}$$

And then, the von Karman strain–displacement relations are applied, thus the in-plane strain vectors are obtained as

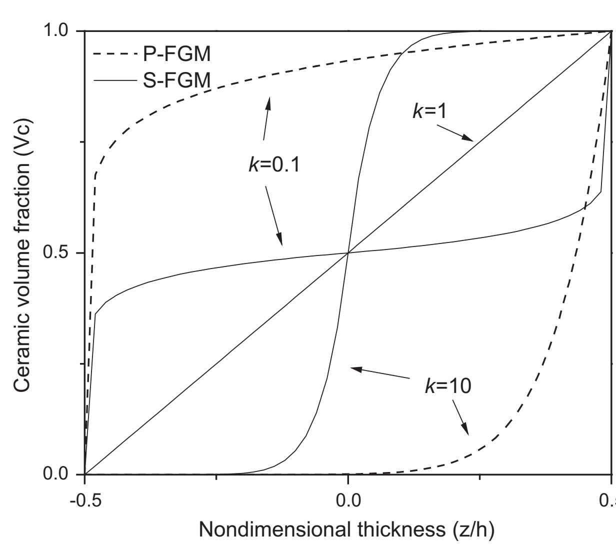

Fig. 1. The variation of the ceramic volume fraction in P- and S-FGMs.