Journal of Sound and Vibration 432 (2018) 155–172

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Effect of static load on vibro-acoustic behaviour of clamped plates with geometric imperfections

Di Wang, Qian Geng, Yueming Li*

State Key Laboratory for Strength and Vibration of Mechanical Structures, Shaanxi Key Laboratory of Environment and Control for Flight Vehicle, School of Aerospace Engineering, Xi'an Jiaotong University, Xi'an, 710049, People's Republic of China

A R T I C L E I N F O

Article history:
Received 29 September 2017
Received in revised form 13 February 2018
Accepted 8 June 2018

Handling Editor: J. Astley

Keywords:
Vibro-acoustic characteristics
Static load effect
Geometric imperfection
Two-step theoretical approach
Experimental validation
FEM/BEM validation

A B S T R A C T

The effect of static load on the vibro-acoustic behaviour of clamped rectangular plates with various geometric imperfections is further investigated in this paper. An effective method applying static load on the plate subjected to dynamic excitations is proposed in the experiment. The Von Karman nonlinear incremental strain-displacement relationship is utilized to describe the large deflection and initial geometric imperfection. Based on the assumed mode method and Hamilton's principle, the nonlinear vibration governing equations of an imperfect plate considering the added effect in the experimental implementation are formulated. Firstly, the nonlinear static deflection is solved iteratively. Then the tangent stiffness matrix is utilized to calculate the linear vibration at the equivalent static position. The acoustic radiation can be derived hereof by Rayleigh integral. The theoretical, numerical and experimental results coincide well. The results show that the natural frequencies of the imperfect plate are higher than those of the original flat one. Under static load, different from the flat plate which is stiffened, the imperfection may lead to either stiffening or softening of the plate depending on the imperfection shape and the static load direction. And the vibro-acoustic characteristics are affected accordingly. It is noted that when the imperfection gets larger, snap-through may occur under static pressure. Furthermore, comparison of vibration characteristics among different load locations with the same static load is also discussed.

1. Introduction

Hypersonic crafts are usually subjected to combination of extreme static load, thermal load, mechanical and acoustic excitations in service [1], which makes the structure design and dynamic analysis of the crafts much more difficult. Static load and thermal load can change the geometry shape and stress state. Thus, the vibro-acoustic behaviour are affected thereof. In addition, plates, the main component of craft structure, are usually not perfectly flat due to structure design and machining craftsmanship.

Up till now, lots of efforts have been made on the structure vibration and acoustic radiation research [2]. Park et al. [3] studied the effects of support properties on the sound radiation of rectangular plates, finding that the optimal support stiffness minimizing the radiated sound power is smaller than that minimizing the velocity response. The combined FEM/

* Corresponding author.
E-mail address: liyueming@mail.xjtu.edu.cn (Y. Li).

https://doi.org/10.1016/j.jsv.2018.06.019

BEM technique was validated to be effective in calculating the vibration and acoustic radiation of structures in the air [4] and underwater [5]. Jeyaraj et al. used the combined FEM/BEM technique to investigate the dynamic and acoustic response characteristics of isotropic [6], fiber-reinforced composite [7] and viscoelastic sandwich [8] plates in thermal environments, in which the thermal stress effect is discussed in detail. Geng et al. [9–11] theoretically studied the thermal effects on the vibro-acoustic characteristics of simply supported and clamped plates, and the numerical and experimental analyses are also conducted for validation. Using equivalent non-classical theory, Liu and Li [12] derived the vibration and acoustic responses of thermally loaded simply supported sandwich plates. Based on the first-order shear deformation plate theory, Li and Li [13] carried out analytical studies on the vibration and sound radiation of composite plates with thermal effect. Piecewise shear deformation theory was proposed by Li et al. and were applied for the vibration and acoustic responses analysis of composite and sandwich panels under thermal environment through analytical [14,15] and FEM [16] formulation. The above researches discussed in depth the effect of stiffness reduction caused by thermal stress on the vibro-acoustic characteristics of various plates in pre-buckling state. The results showed that with the temperature increasing, the natural frequencies decrease and the vibration and acoustic radiation frequency responses shift towards lower frequency range.

Similar to the thermal effect, the static load also affects the dynamic behaviour of the structure a lot. Usually, both the stress state and geometry of the structure will be changed under static load. Takabatake presented the inner stress effect caused by dead load on the static deflections of elastic beams [17] and plates [18] through analytical approach. He also theoretically investigated the natural frequencies and vibration responses of beams [19,21] and plates [20] including inner stress effect under dead load. The results showed that the natural frequencies increase when the inner stress effect of static load is included. And the increasing trends were also validated by Zhou and Zhu [22] using a load-induced stiffness matrix based finite element method. The geometry deformation is also shown to be a key factor in Geng's [23] experiment about the vibro-acoustic behaviour of a thermally post-buckled plate. He found that the natural frequencies begin to increase in the post-buckling state, which means that the thermally buckled deformation plays a more important role than thermal stress. The stiffening effect of the buckled deformation was also illustrated in FEM analyses of various plates in thermally buckling state [24–26]. Du et al. [27] analyzed the vibro-acoustic characteristics of laminated plates with temperature gradient along thickness. The results indicated that the resonant frequency increases with the increment of deflection caused by temperature gradient. Alfosail et al. adopted Galerkin method to study the linear natural characteristics [28] and nonlinear vibration [29] of statically deformed inclined risers under self-weight. Moreover, the effect of geometric imperfections on the nonlinear vibration of different plates [30–33] and circular cylindrical panels [34] were also investigated through theoretical and experimental approaches.

Above all, few researchers focused on the vibro-acoustic behaviour of imperfect plates under static load. The objective of this paper is to develop experimental and theoretical approaches to investigate the effect of static load on the vibration and acoustic radiation characteristics of clamped plates with geometric imperfections. An effective method applying static load on the plate subjected to dynamic excitations is proposed. The theoretical formulation is derived considering the added effect in the experimental implementation. FEM calculation is carried out to validate the theoretical solution. Effect of static load on the vibro-acoustic characteristics of plates with various geometry imperfections is discussed in detail. The experimental results, which are conducted under the theoretical guidance, show good agreements with the theoretical and numerical results.

2. Method of applying static load in the experiment

Up till now, few researchers have done the related research through experimental approach. It is difficult to apply static load on the structures subjected to vibration and acoustic excitations for the following three reasons: (1) the loading equipment may bring added mass and stiffness, (2) it is difficult to keep the static load steady when the plate is excited by dynamic loads, (3) the loading equipment may affect the acoustic field around the plate.

Fig. 1(a) shows the geometric model studied in this paper. A clamped rectangular plate under static load F^s is subjected to dynamic load $F^d(t)$. Considering the difficulties above, an effective method is proposed as shown in Fig. 1(b). An elastic spring, of which the tensile stiffness is k, is fixed at the static load location of the plate with one end. The other end is stretched to a distance of dl to apply a static load of $F^s = k \times dl$ on the plate. As the tensile stiffness of spring is relatively small and the present research focuses on linear vibration with small amplitude, the variation of the static load can be designed to be negligible by selecting a right spring. At the same time, the acoustic field above the plate is not affected by the static load application.

To apply static load, the spring also acts as an elastic constraint to the plate. In the next section, the effect of the elastic constraint is analyzed by theoretical approach to find the appropriate spring selection criteria in the experiment and to validate the effectiveness of the proposed method.

3. Theoretical formulation

Consider a clamped plate as shown in Fig. 1, of which the length, width and thickness are l_x, l_y and h respectively. $F^d(t)$ is the dynamic load. The spring with tensile stiffness coefficient k is stretched to a distance of dl to apply the static load $F^s = k \times dl$ on the plate.

Assume that the displacements of the plate are expressed as: