Multimode damping of thin plates by arrays of separately shunted piezoelectric patches

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Abstract

Two-dimensional thin plates are widely used in many aerospace, automotive and marine applications. Among many methods for the attenuation of vibration in these mechanical structures, piezoelectric shunt damping is a promising way. It enables a compact vibration damping method without adding significant mass and volumetric occupancy. Although shunt damping have been studied extensively in the literature, most of the studies do not provide a formulation for modeling the piezoelectric patches that partially cover the plate surface and scattered on the host structure. In this study, the Rayleigh-Ritz model is used for solving the modal analysis and obtaining the frequency response functions of the electro-mechanical system. The developed model includes mass and stiffness contribution of the piezo-patches. Different from previous studies, each piezo-patch is separately shunted via an electric circuit rather than arranging all the patches in parallel and then connecting all of them to a single electric circuit. For verification of Rayleigh-Ritz method, finite element simulations are performed in ANSYS and compared with the analytical model results. An optimization study is performed by varying number of the patches to improve the shunt damping performance. It was shown that separately shunted configuration is much more effective compared to the parallel arrangement.

Introduction

Two-dimensional thin plates are widely used in many aerospace, automotive and marine applications. Among many methods for the attenuation of vibration in these mechanical structures, piezoelectric shunt damping is a promising way. This techniques have been extensively studied over the past decade as an alternative to the bulky mass-spring-damper systems for attenuating the vibrations of flexible structures. Piezoelectric patches can be directly integrated to plate-like structures, without adding significant mass and volumetric occupancy, and transform the mechanical energy into the electrical energy through various electrical circuit components and as a result, can attenuate the excessive vibrations.

Accurate modeling tools are required for the circuit elements and the host structure to predict the performance of the shunt damping circuit. Hagwood and von Flotow [1] showed that a piezoelectric patch shunted to an inductive circuit forms an electrical resonance, acting as equivalent to a pure mechanical vibration damping system. Other research groups have used a network of multi-modal damping resonant shunt circuits [2], [3]. For broadband vibration control of flexible structures or implemented negative capacitance circuits [4], [5], [6]. For modeling of electromechanical systems, Yoon [7] recently proposed a novel method to model the patches on a thin plate by using Rayleigh-Ritz method.

In this paper, Rayleigh-Ritz model is used for solving the modal analysis and obtaining the frequency response functions of the electro-mechanical system. Each piezo-patch is separately shunted via an electric circuit rather than arranging all the patches in parallel and then connecting all of them to a single electric circuit. For verification of the Rayleigh-Ritz method, system-level finite element simulations are performed in ANSYS and compared with the analytical model results. An optimization study is performed by varying number of the patches to improve the shunt damping performance. Figure 1. shows demonstration of shunt damping via piezoelectric materials.

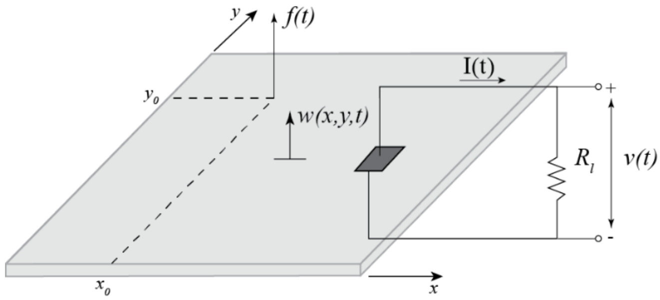

Figure 1: Demonstration of shunt damping via piezoelectric patches

Methods

The fundamental equation for motion for this structure can be seen in equation (1)[8]. For electric equation the equations (2) and (3) are used which (2) present connected configuration and (3) represent separated configuration.

$$\frac{d^2\eta_{rn}(t)}{dt^2} + 2\omega_{rn}\xi_{rn}\frac{d\eta_{rn}(t)}{dt} + \omega_{rn}{}^2\mu_{rn}(t) - \sum_{k=1}^{K}\theta_{rn}{}^{k}v_k(t) = f_{rn}(t) \tag{1}$$

$$\sum_{k=1}^{n}(C_p)_k\left(\frac{dv(t)}{dt}\right) + \frac{v(t)}{Z_l} = \sum_{k=1}^{n} i_k(t) \tag{2}$$

$$(C_p)_k\left(\frac{dv_k(t)}{dt}\right) + \frac{v_k(t)}{(Z_l)_k} = i_k(t) \tag{3}$$

In these equations, η_{rn} is the modal response, ω_{rn} is natural frequency, ξ_{rn} is structural damping, θ_{rn} [9]–[11]is coupling factor, v is voltage, f_{rn} is modal force, C_p is capacitance of piezoelctric patch, Z_l is shunted mpdence, i_k is modal currenct.

Validation via FEM

Commercial finite element analysis (FEA) software ANSYS is used for validating the modal solutions obtained using the analytical model. The plate is meshed with 20-node structural solid elements (SOLID 186). The piezo-patches are meshed with 20-node coupled field solid elements (SOLID 226). The host structure and the piezo-patches are bonded. External resistive load connected to piezo-patches is modeled with piezoelectric circuit element (CIRCU 94). Figure 2 shows this demonstration.

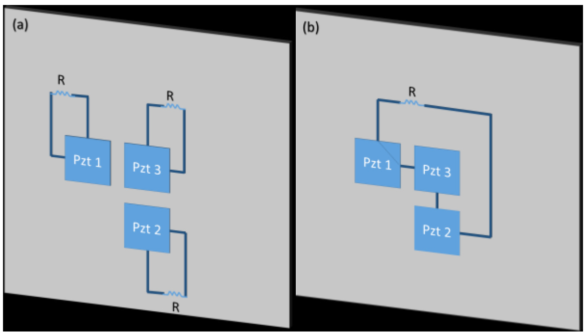

Figure 2. Host plate with all four edges clamped (CCCC) boundary conditions and the structurally integrated piezoelectric patches in (a) separated patches, (b) connected.

The velocities of the 36 points (equally spaced on the plate) under the effect of the excitation are averaged and shown as the output in the following figures. The results show that separated connection have better shunt damping compared to connected patches especially on modes 2 and 3.

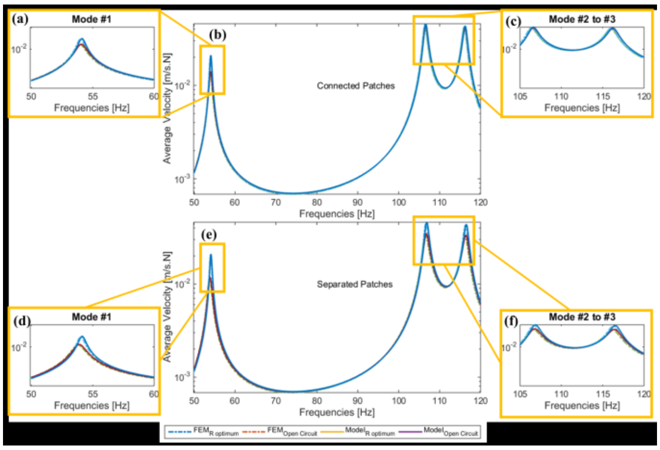

Figure 3. Average velocity FRF for (a) first mode on connected patches, (d) first mode on separated patches, (c) second and third mode on connected patches, (f) second and third mode on separated patches, (b) first three modes on connected patches, (e) first three modes on separated patches, (-.-.-) FEM on optimized R, (-.-.-) FEM on Open circuit, (—) Model on optimized R, (—)Model on open circuit.

Effect of number of patches

In this model, 5 sequences of number of patches are selected, in each sequence, a similar area which has ration of 0.92 of total plate is chosen. Figure 3 shows the models.

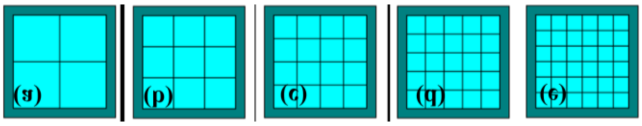

Figure 3. Patches model (a) 4 patches, (b) 9 patches, (c) 16 patches, (d) 25 patches, (e) 36 patches

Figure 4 shows the vibration attenuation for first mode on the patches number sequences. It is shown when the number of patches increases the vibration attenuation is much higher.

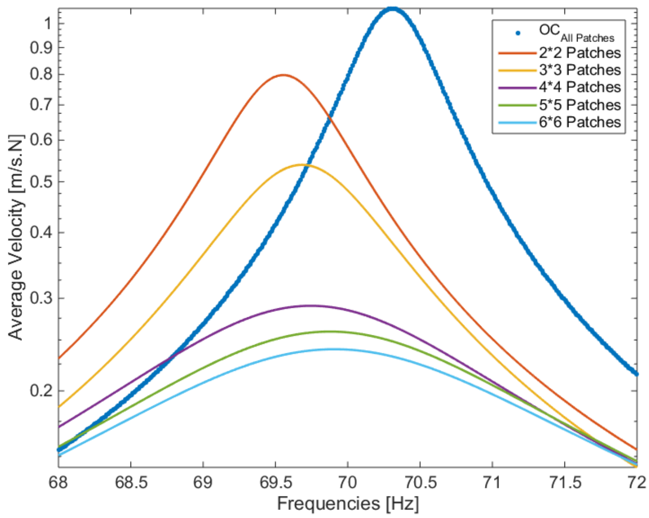

Figure 4. Patches model shunt damping performance

Conclusion

It was shown that piezoelectric shunt damping is an effective method for vibration attenuation when it is used on plate-like structures. An analytical model of the electromechanical system was developed for predicting the shunt damping performance of the separated and connected piezo configurations. The model results were validated with FEM results and it was shown that separately shunted configuration is much more effective compared to the parallel arrangement. It was also shown that when the number of patches increases the vibration attenuation is much higher.

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