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Optimal Design of Smart Panel using Taguchi Method

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Key Words: Taguchi Method, Piezoelectric Shunt Damping, Admittance Analysis.

ABSTRACT

Taguchi method is used to determine the optimal configuration of PZT (Lead Zirconate-Titanate) patch on the host structure for improving the performance of piezoelectric shunt system. The charges generated on the surface of PZT patch are selected to be the objective function in the Taguchi method. Full three dimensional finite element models are used to simulate vibration of smart panel and to obtain the admittance of the piezoelectric shunt system. Using Taguchi method in Minitab, the optimal model is obtained. The experiment with piezoelectric shunt circuit is performed to verify the validity of the optimal model comparing with initial model.

1. INTRODUCTION

Piezoelectric materials have been introduced as passive damping materials to overcome the limits of viscoelastic materials. The main reason which we use it is the vibration suppression of structure can be achieved through its mechanical-electrical coupling effect, that is, it can transfer the mechanical energy to electrical energy when it is strained, and vice versa.

Smart material and structure have been extensively used as active technology to suppress the noise generated by the working components. Piezo ceramics (PZT) are widely used in order to fulfill the related object. For this, many researches have been conducted numerically and experimentally [1-4].

There are many parameters that affect the functions of related system in smart panel. These parameters include the number, size, shape and locations of piezoelectric patches. Thus, the efforts that optimize these parameters are necessary for the system to achieve high performance. So far, some efforts have been devoted to finding optimal placement of PZT patches. With optimal placement of PZT patches, a remarkable reduction of the transmitted noise can be observed at resonant frequencies[4].

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As mentioned before, to improve the performance of piezoelectric shunt system requires the high-energy conversion rate from mechanical energy of piezoelectric structure to electrical energy. Therefore, it is important to analyze admittance, which represents the electro-mechanical characteristic of piezoelectric structure and the ease with alternating current flow through a complex circuit system [3]. In the present study, the relation between admittance in piezoelectric structure and dissipated energy in shunt circuit is considered in single mode piezoelectric shunt system and then admittance is adopted as a design index in piezoelectric structure.

This paper aims at optimally designing the placement and size of the PZT patches on the host structure using Taguchi method based on the admittance analysis. There exists relationship between admittance in open circuit and dissipated energy by the shunt circuit and it is shown that admittance can be defined as a design index of piezoelectric structure. Taguchi method [5,6] is selected in order to optimize the placement of PZT patch. The combination of standard experimentation design techniques and analysis method in Taguchi approach produces consistency and reproducibility rarely found in any statistical method.

2. MODELING AND TAGUCHI OPTIMAL DESIGN

In the present paper, a flat aluminum plate with surface-bonded piezoelectric patch is studied. The host plate is clamped on the boundaries as shown in Figure 1. During vibration, the PZT patch will produce electric current in it and the charges will emerge on the surface of the electrode. At the same time, at resonance frequencies, the values of current and charge are excessively larger than the ones at other frequencies. The larger values of current and charge can represent the vibration energy at resonance frequencies and it is reported that the absorbed energy in piezoelectric shunt circuit is proportional to the generated charges of smart panel [1]. The charge is proportional to admittance since admittance is current divided by voltage. Therefore, the charge values are used as an objective function in order to obtain the optimal configuration by Taguchi method.

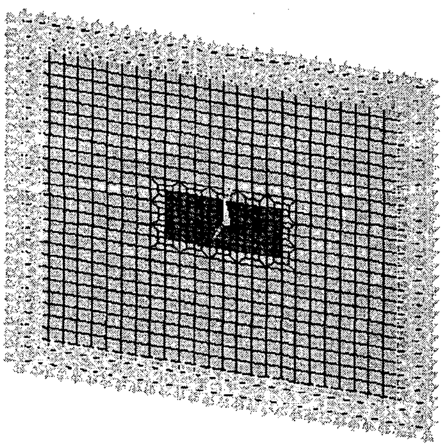


Figure 1.Aluminum plate with single PZT

2.1 Formulation of structure and piezoelectric patch

Finite element analysis is an effective method for analysis of structural response, because it is applicable to arbitrary shapes and geometries. The equation of motion of the piezoelectric plate in matrix form can be expressed as follow[7].

$$\begin{Bmatrix} [M] & [0] \\ [0] & [0] \end{Bmatrix} \begin{Bmatrix} [\ddot{u}] \\ [\ddot{\phi}] \end{Bmatrix} + \begin{Bmatrix} [D] & [0] \\ [0] & [0] \end{Bmatrix} \begin{Bmatrix} [\dot{u}] \\ [\dot{\phi}] \end{Bmatrix} + \begin{Bmatrix} [K] & [K_{u\phi}] \\ [K_{u\phi}]^t & [K_{\phi}] \end{Bmatrix} \begin{Bmatrix} [u] \\ [\phi] \end{Bmatrix} = \begin{Bmatrix} [F] \\ [Q] \end{Bmatrix} \quad (1)$$

$$|Y| = \left|\frac{I}{V}\right|, \quad I = j\omega \sum_i Q_i \quad (2)$$

where,

$[F]$, $[u]$: vector of nodal structural forces and mechanical displacements

$[M]$, $[D]$, $[K]$: structural mass, damping and stiffness matrix

$[Q]$, $[\phi]$: vector of nodal electrical charges and potential

$[K_{u\phi}]$, $[K_{\phi}]$: piezoelectric coupling and dielectric conductivity matrix, " t " : transposed

Y, I, V : admittance, current and voltage

Q_i : the point charge of the i-th node on the electrode.

To formulate above equation, commercial finite element package, ANSYS, is used. From the above equations, mode shapes and natural frequencies of aluminum plate with and without piezoelectric patch are analyzed and admittance of piezoelectric structure is obtained.

2.2 Taguchi method for optimal design

Taguchi's approach complements two important areas. The first, a set of orthogonal arrays is defined, which can be employed for many experimental situations and the second, a standard method for analysis of results is devised. The combination of standard experimentation design techniques and analysis method in Taguchi approach produces consistency and reproducibility. For simplicity, the location (X and Y coordinates) and the size (width W and length L) of piezoelectric patch are defined as the design parameters and every parameter has three levels (Table1). L9 orthogonal arrays are used in the optimization. After using Taguchi analysis in Minitab, one can find an optimal configuration of the piezoelectric patch on the plate.

In Taguchi method, the signal to noise ratio (S/N ratio) is used to measure the sensitivity of the quality characteristic being investigated in a controlled manner. Generally, the target of the experimental method is to determine the highest S/N ratio for the result. A high S/N ratio shows the best dataset on the basis of minimum deviation. The results of S/N ratio were used to compute the main effects of the individual factors. The S/N ratio is usually calculated by the equation:

$$S/N = -10\log_{10}(MSD) \quad (3)$$

where MSD means the mean squared deviation of the set.

Table 1. Table of Control Factors

Control factors	Levels		
	1	2	3
X (coordinate) (mm)	0	25	50
Y (coordinate) (mm)	0	25	50
L (PZT length) (mm)	50	75	100
W (PZT width) (mm)	50	75	100

3. NUMERICAL RESULTS

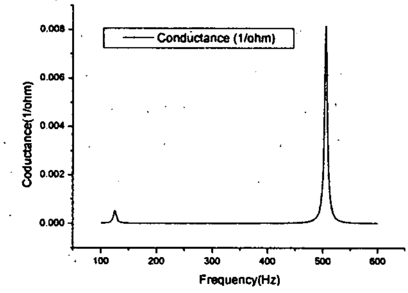
A square aluminum plate with surface-bonded PZT patch is considered as shown in Fig. 1. The size of the aluminum plate is 350mmx350mmX1.5mm. We selected PZT-5H as the shunt damping material and it is bonded on the surface of the aluminum plate. The size of PZT patch is selected according to the configuration in Table 1. The thickness of PZT patches is all 0.5mm.

3.1 Numerical results using FEM analysis

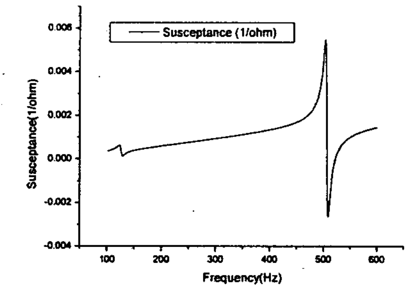
Modal and harmonic analysis are used in order to obtain the mode shapes of the structure and the admittance values at different natural frequencies. To discretize piezoelectric patch and aluminum plate to finite element, element type solid 5 in ANSYS is used for piezoelectric patch and solid 45 for aluminum plate, respectively. The first, in terms of modal analysis, the mode shapes and natural frequencies are derived. From the modal analysis, the modes that will be suppressed are designated. Then, harmonic analysis is followed to obtain the values of admittances and charges. Admittance is consisted of real and imaginary values, i.e., conductance and susceptance. Figure 2 presents admittance of initial design obtained by FEM.

3.2 Numerical results using Taguchi Method

The Minitab is a software specially designed for statistics. The DOE (Design of Experiment) module including Taguchi method application is the part of it. The parameters of which Taguchi method makes use are selected from table 1. After running Minitab, one can obtain the optimal result from the main effect plots for S/N ratio (Fig. 3) and S/N noise values (Table 2). According to the "larger is better", the optimal result is (1 1 3 3) case, that is the PZT patch will lie the center of structure and size is 100mmx100mm.



(a) conductance



(b) Susceptance

Figure 2. Admittance of initial design

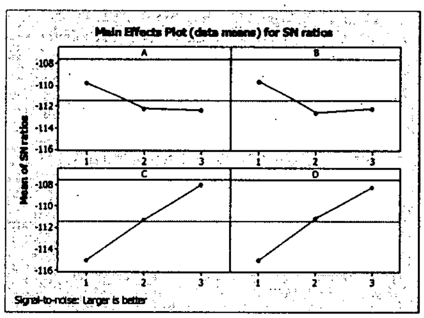


Figure 3. All charge main effects plots for S/N ratio

Table 2. Response Table for Signal to Noise Ratios

Level	Factors			
	A	B	C	D
1	-109.8	-109.6	-115.1	-115.0
2	-112.2	-112.6	-111.3	-111.2
3	-112.4	-112.2	-108.0	-108.2
Result	1	1	3	3

4. EXPERIMENTS

Two vibration suppression tests of initial and optimal design set were conducted for the validation of

Taguchi optimal design. The initial configuration of piezoelectric patch was 100mmx50mmx0.5mm and located at the center of aluminum plate. The optimal configuration of piezoelectric patch obtained by Taguchi method was 100mmx 100mmx0.5mm and also located at the center of plate. Resonant shunt circuit was connected to the piezoelectric patch. The first and fifth modes were selected as target modes. Figures 4 and 5 show FRF responses with and without piezoelectric shunt obtained by accelerometer at the center of piezoelectric patch. Comparison of shunt performance is listed in table 4. In optimal piezoelectric configuration, the magnitudes of noise reduction are 8dB at first mode and 24dB at fifth mode, respectively. It is observed that the performance of piezoelectric shunt is improved as 33 % in first mode and 20 % in fifth mode compared to the initial configuration.

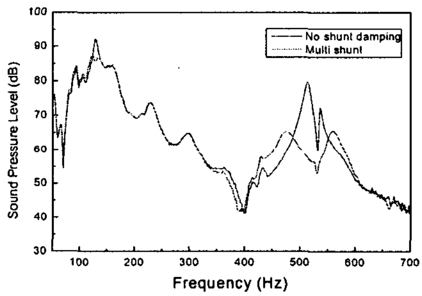


Figure 4. FRF responses of initial configuration

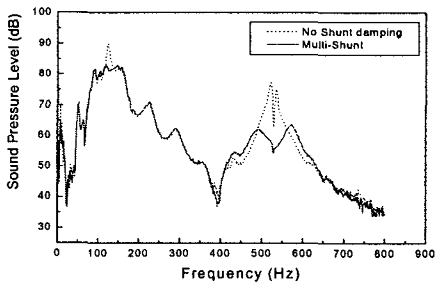


Figure 5. FRF responses of optimal configuration

Table 3. Comparisons of the piezoelectric shunt performance between initial and optimal model

Mode Number	Initial Model		Optimal Model	
1	129 Hz	-6dB	126 Hz	-8dB
5	503 Hz	-20dB	506 Hz	-24dB

5. CONCLUSION

Taguchi method is used to obtain the optimal placement of piezoelectric patch bonded on the smart panel. Charge values generated in the piezoelectric patch are used as an objective function in optimization procedure. Four parameters and three levels for each parameter are defined in the Taguchi optimal design. It means that $3^4=81$ trials are required for obtaining the optimal configuration. However, Taguchi method just used 9 trials instead of all cases and obtained the optimal result. It represents that the method is efficient and effective for the optimal design. The experimental results proved that the optimal configuration obtained by Taguchi method improved the performance of piezoelectric shunt system. Using optimal configuration, the performance of piezoelectric shunt is improved as 33 % in first mode and 20 % in fifth mode compared to the initial configuration.

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