Design of Control System for Active Vibration Suppression of Trapezoidal Plate

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Abstract

An active vibration control system is proposed for suppressing the small amplitude plate vibration. The structure under study is a vibrating trapezoidal plate, having a constant thickness, to which MFC (Micro Fiber Composite) actuator is bonded. It was assumed, that the plate clamped at one edge is excited by a uniform periodic force generated by a loudspeaker. The control problem lies in using MFC actuator to reduce the plate vibrations. For the system under consideration the mathematical model obtained on the base of parametric identification method is constructed. This part of the research was done with the help of Polytec laser vibrometer. The apparatus is highly advanced tool that allows measurement of vibration of examined structure. With transfer function model obtained in identification process, using Matlabs Identification Toolbox, feedback control laws was created for changing response of the system in desired way. There are many ways to model controller having mathematical model of the object. In this article, authors propose approach to design an effective controller for vibration suppression of a trapezoidal plate with the use of the pole placement method in graphical SISOTool environment. This article describes concept, results of simulation tests and implementation for the designed controller.

Keywords: trapezoidal plate, active vibration control, MFC element, ARX model

1. Introduction

The issue of low frequency vibrations control is an extremely important problem that should be considered both at the design stage and later during their operation. The constant advancement of information technology allows real-time systems to be designed more and more effectively [2, 3, 13]. Working with efficient data acquisition cards, give the possibility to simulate, implement and test control systems. Rapid prototyping of control systems enables software such as Altium Designer, LabView, MATLAB/Simulink and many more. This article describes a study in which the xPC Target platform [8] was used, cooperating with the MATLAB environment, to design and implement a vibration control system for a trapezoidal plate using a collocated MFC sensor / actuator.

In general, vibration control systems can be divided into two groups: passive and active methods [7]. The first focuses on reducing adverse vibrations by modifying the parameters and structures of the systems. Active methods, unlike passive ones, based mainly on storage and energy dissipation, compensate vibrations through own production. Such solutions consist in connecting an energy source to the external system.

Such element can be placed anywhere in the device and its work in such a way as to generate or absorb vibroacoustic energy to reduce redundant vibrations.

The most important element of active vibration reduction systems (AVC) are sensors and actuators. They allows you to collect information about the subject of the test, so it can be used later to create a vibration compensation algorithm. Their construction should be considered in such a way that they will not negatively affect the system in which they will be mounted, for example by increasing stiffness or adding weight. Such element should be characterized by low mass, high efficiency, long life and small size. Piezoelectric elements come out against this challenge [1]. Smart Materials MFC are a new type of piezoelectric tools that sensors and actuators are made of. The mechanical and electrical properties of MFC have been described in many articles, confirming their effectiveness and reliability [10]. Researchers dealing with the issue indicate the placement of sensory and executive elements as extremely important. Improper deployment can cause lack of observabiliy and controlability, which strongly affect the quality of the control system [12].

Easiest way to create a closed-loop system contains two steps. The first is to identify the mathematical model of the object being studied. The second step is to use the obtained model to design the controller. During the research, the authors determined the resonance frequencies, harmonics of the tested board and designed tuned controllers to suppress them. For this purpose, the generated ARX model was used by the standard LMS algorithm from MATLAB System Identification Tools. This article describes the method of creating an effective system of vibration control of a trapezoidal plate, using SISO Tool from MATLAB software. The research stand was based on the xPC Target platform, controlling the workstation equipped with two multifunction boards. At the end, the results of both simulations and preliminary results of the real application of the designed systems will be presented.

2. Construction of the stand

The object that was tested was an aluminum trapezoidal plate with dimensions as follows: longer base 63cm, shorter base 21 cm, height 44 cm [6]. It was attached for a longer base to iron-cast cuboid with a height of 90 cm and a weight of about 120 kg. A laser vibrometer measuring head was placed above the station. A rectangular MFC M-8557-S1 [11] element with dimensions of 85 x 47 mm was glued to the tested board.

In the first part of the experiment, its task was to transfer vibrations to the object and acquire data for the needs of the identification process. Later, after connecting to the station with xPCTarget, using the collocated sensor and actuator, it served as a vibration sensor of the board and transmitted to it the signal of the vibration damping regulator.

The location of the element on the plate was selected based on the vibrometer tests, in order to simulate the exemplary work and effectively vibrations reduction.

Figure 1. Research object with attached MFC sensor/actuator

All elements of the measurement system are shown on Fig. 2. The stand consisted of: 1 – vibrometer measuring head, 2 – LCD monitor, 3 – computer station with scanning software, 4 – cuboid body, 5 – trapezoidal plate, 6 – loudspeaker.

Figure 2. Testing stand

3. Measurement of vibration

To create a mathematical model of the tested object, the identification procedure should be performed. In order to understand the acoustic properties of the test panel, a laser vibrometer test was carried out. It involves the imposition of a virtual grid of measurement points on the object, and then inducing vibrations with a specific signal to collect data about the object's response. The plate was excited to vibration with a signal of constant amplitude and a changing frequency in the range of 20 to 500 Hz. The device's software generated an animation showing the disc response to the given stimulation. The result is shown below.

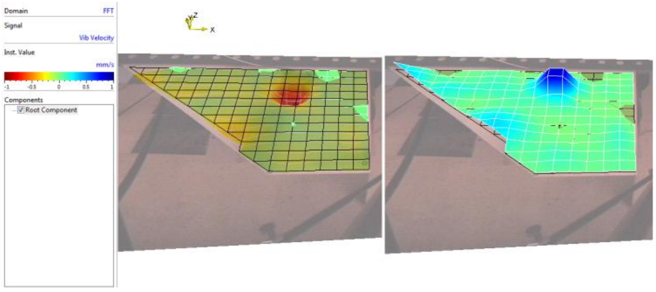

Figure 3. Resonant model shape. Maximum velocity amplitude

FFT analysis allowed determining the resonant frequencies of the plate. The reduction of vibration amplitude is the result of the operation of control signals determined by the designed controller.

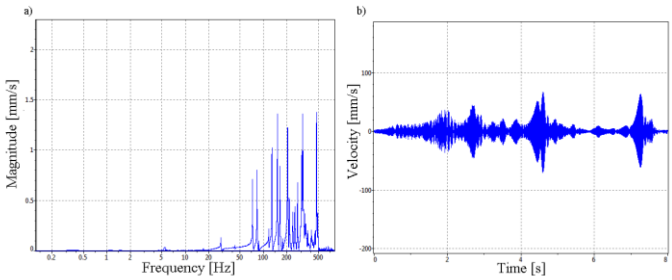

Figure 4. Diagrams: a) resonant frequencies of the plate;
b) plate response for chirp excitation of 20-500 Hz

The reduction of the largest vibration amplitude at the first resonant frequency usually causes the reduction of other harmonics with smaller amplitudes occurring at different frequencies. With this in mind, the 73 Hz and 315 Hz frequencies were chosen for the digital controller design.

4. Identification of the object

In order to find the parameters of the digital controller one should identify the object subject to control, i.e. determine its mathematical model. It defines the behavior of the object under certain conditions, which are described by the input and output of the object at present and in the past. Naturally, the model is a certain approximation of the actual object. Different types of models are used depending on the purpose of the model being created and the structure of the object being identified. Assuming that the sampled signal values can be related through the linear difference equation given by Eq.(1) [9]:

$$\begin{aligned} & y(k) + a_1 y(k-1) + a_{nA} y(k-nA) \ldots \\ = \; & b_1 u(k-d) + b_{nB} u(k-d-nB+1) + e(k), \end{aligned} \tag{1}$$

where $y(k)$ and $u(k)$ are respectively the output and input in discrete time $k = 1, 2, 3,...$; nA is the number of poles, nB is number of zeros, d indicates number of samples before input reacts to system output and $e(k)$ stands for the noise.

Idea of active vibration suppression can be generally characterized by the diagram (Fig. 5). Plant is described by the transfer function G_0, the actuator-to-error transfer path. Used MFC element (controller) uses error sensor data to generate actuator drive signal to reduce plate vibration. Autoregressive model with exogenous input (ARX) which was shown above (1) can be represented using z^{-1} operator as Eq.(2):

$$y(k) = \frac{B(z^{-1})}{A(z^{-1})}u(k-d) + \frac{1}{A(z^{-1})}e(k), \quad (2)$$

where:

$$A(z) = 1 + a_1 z^{-1} + \ldots + a_{nA} z^{-nA}, \quad (3)$$

$$B(z) = b_1 + b_2 z^{-1} + \ldots + b_{nB} z^{-nB+1} \quad (4)$$

is considered as a base model of the vibrating planar trapezoidal plate.

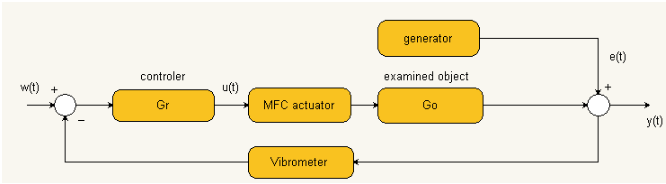

Figure 5. Control system diagram

In order to obtain polynomial coefficients in (3), (4) authors used sine signals with frequencies obtained in previous section (73 Hz and 315 Hz) and chirp signal which frequency changes from 20 to 500 Hz. Those three identification processes led to design three digital controllers, two tuned to reduce chosen resonant frequencies and one which reduce whole frequency band. The accuracy of the model derived was estimated according to the MATLAB criterion of *best fit* defined as:

$$BEST_{FIT} = (1 - |y - y_{model}| \,/\, |\, y - mean(y)|) * 100\%, \quad (5)$$

where y stands for measured output, y_{model} is simulated or predicted model output, and $mean(y)$ designed mean or measured output. Results of identification process are shown below.

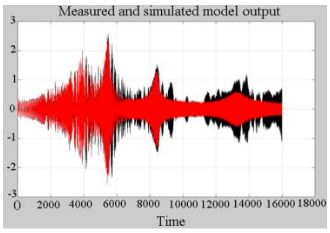

Figure 6. Identification results for chirp signal of 20-500 Hz

5. Controller design

Having transfer function obtained in identification process we can careate a feedback control law to change the response of the system in a desired way [2, 4]. In order to fit the established criterion of our closed-loop system we were looking for a controller transfer function presented as the well-adjusted ratio of polynomials $Q(z^{-1})/P(z^{-1})$. Using this technique, authors have to bear in mind that the requirement of closed-loops systems is to keep polynomial roots in the left-hand plane.

Using SISO Designing Tool software pole placement was done by the designer. Finally, location of poles and zeros for the closed loop systems is shown in the figure below.

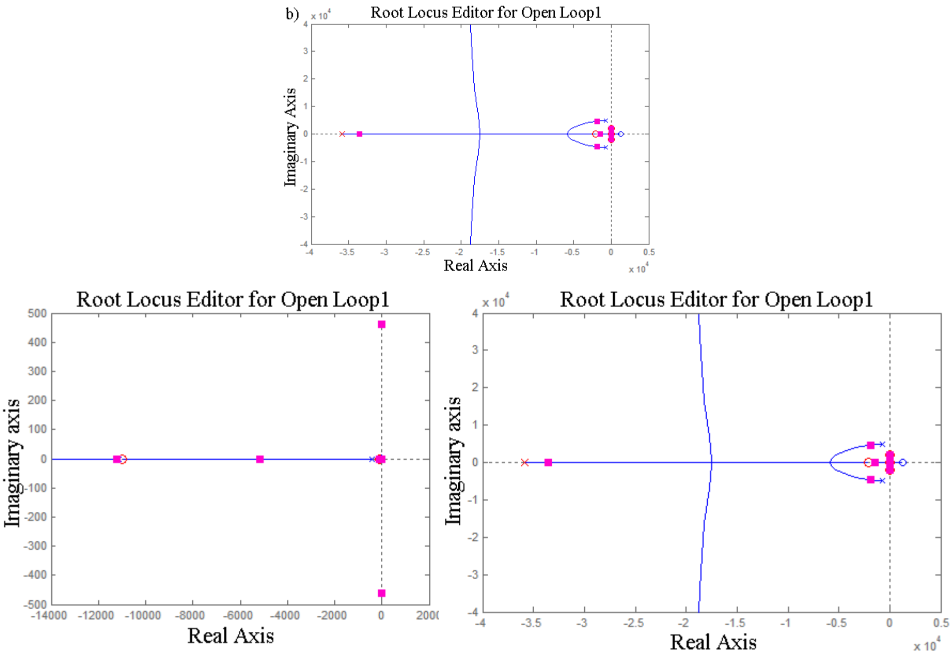

Figure 8. Location of zeros and poles of the system: a) identified 73 Hz, b) identified 315 Hz, c) identified chirp

Obtained transfer function of controller for control system based on identified 73 Hz sine signal presents as follow:

$$G_C = \frac{-4.634z^2 + 2.214z - 2.04}{z^2 - 1.992z + 0.9921} \tag{6}$$

Using MATLAB/Simulink software simulations of designed control systems was done. Acting of designed controller has been verified by testing behavior of the plate driven by the sinusoidal signal with frequency 73 and 315 Hz. Results are presented in Fig. 9.

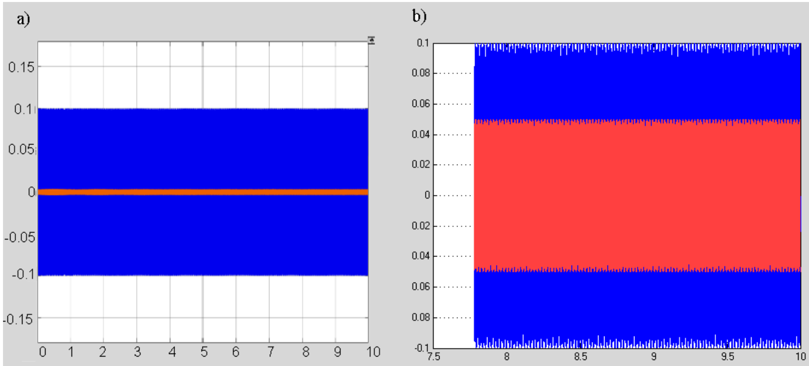

Figure 9. Simulation results for designed controller for: a) 73 Hz excitation, plate vibration reduced by about 90%, b) 315 Hz excitation, plate response reduced by about 50%. Both: blue color – open loop, red – closed loop system

6. Preliminary results of implementation

Designed controller has been implemented and tested on a real-time platform – PowerDAQ with xPC Target environment supervising action of two multifunctional boards. First card (PD2-AO-8/16) is the Analog Output Module used for controlling MFC actuators. The sampling rate at 100 kS/s per channel and 16 bit converter resolution were sufficient to completely control the operation of the actuators. To adjust the output voltage D/A cards to voltage level of the MFC actuator (from 1,500 V to -500V), it was necessary to use a high-voltage amplifier (HVA 1500 50/4), which processes the signal in the frequency range from 0 Hz to 16 kHz. The second card (PD2-MFS-8-500/14) contains analog inputs with 14-bit A/D transducer. One of the inputs of this card, which was connected directly to MFC element (M-8557-S1), provides voltage values within the range of ± 10 V and acceptable sampling rate [3]. Initial results of implementation are shown below. For the purpose of the experiment, plate was excited by sine wave signal, with frequency of 73 Hz and amplitude of 1 V. Obtained results shows substantial reduction, giving prospects for future research. Plate vibration was reduced to about 0.2 V i.e. 80% of initial excitation.

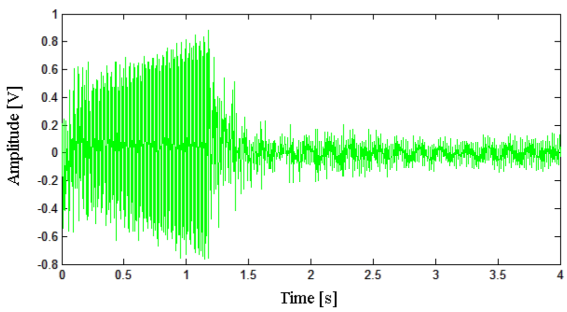

Figure 9. Initial results of tested control system

7. Conclusions

The main goal of the research was to investigate capability of MFC elements to suppress trapezoidal plate vibrations. The paper shows next steps in process of designing control system. Described stand is based on xPCTarget platform watching over two multifunctional boards. Feedback control is realized with rectangular MFC element attached to the plate. During research, the mathematical model was obtained and its transfer function was used for designing digital controller with the pole-placement method. Results of experiment, both simulation and real test confirmed effectiveness of chosen method and show that the plate displacement can be considerably suppressed.

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