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MFC Sensors and Actuators in Active Vibration Control of the Circular Plate

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In this paper, the MFC sensor and actuators are applied to suppress circular plate vibrations. It is assumed that the system to be regulated is unknown. The mathematical model of the plate was obtained on the base of registration of a system response on a fixed excitation. For the estimation of the system's behaviour the ARX identification method was used to derive the linear model in the form of a transfer function of the order nine. The obtained model is then used to develop the linear feedback control algorithm for the cancellation of vibration by using the MFC star-shaped actuator (SIMO system). The MFC elements location is dealt with in this study with the use of a laser scanning vibrometer. The control schemes presented have the ability to compute the control effort and to apply it to the actuator within one sampling period. This control scheme is then illustrated through some numerical examples with simulations modelling the designed controller. The paper also describes the experimental results of the designed control system. Finally, the results obtained for the considered plate show that in the chosen frequency limit the designed structure of a closed-loop system with MFC elements provides a substantial vibration suppression.

Keywords: MFC elements, active methods, parametric identification, ARX model, plate vibration suppression.

1. Introduction

An extremely useful MFC (*Macro-Fiber Composite*) technology has arisen from an almost completely empirical design. Recognizing the superior qualities of this new kind of piezocomposites for sensing and actuating, researchers have adopted the MFCs for a full spectrum of the structural control, the vibration suppression, and structural monitoring applications. Nowadays, the MFC elements are commonly used in different disciplines of science, such as monitoring the condition of the structure (called Structural Health Monitoring) and evaluation of its reliability, suppressing the vibration of beams or plates (Kos *et al.*, 2013; Mazan, Leniowska, 2014), energy harvesting (Song *et al.*, 2010), etc. The MFC actuator package employs piezoceramic fibers locked in an epoxy matrix and sandwiched between two arrays of electrodes. In contrast with the round fiber geometry of other piezocomposites, the piezoelectric fibers in MFCs have rectangular cross-sections and are assembled in the MFC package with regular spacing and parallel alignment. Due to its high conformability, high flexibility, and low mass, the MFC does not introduce significant mass or stiffness coupling to host structures. Numerous papers concentrate on the mathematical modelling of smart piezoelectric materials, where the explanation of the mechanical and electronic properties, as well as the actuation and sensing capabilities of the MFC, are investigated.

A very important issue raised by many researchers is the way of placing the sensors and actuators on a vibrating plate. Wrong placement of such elements can cause a lack of observability and controllability, what strongly affects the quality of the control system.

Generally, in order to maximize the performance of the damping device, the placement and size of the transducer must be optimized. The coupling coefficient of the system can be influenced by the material properties of the piezoelectric element, but also by the placement within the structure and the size of the transducer (Neubauer *et al.*, 2012).

There are several methods of finding the desired location of sensors and actuators. One of them consists in combining optimization of actuators/sensors locations and controller parameters. Some authors propose a quadratic cost function taking into account the measurement error and control energy (Ramesh Kumar, Narayanan, 2008).

In the second approach, the optimal locations are obtained independently of the controller definition. The authors propose a method for the maximization of a controllability/observability criterion using the gramian matrices (Hac, Liu, 1993). For the proper location of the sensors and actuators a genetic algorithm can be used (Bruant *et al.*, 2010).

To determine the best location for MFC elements, the experimental methods can also be used. Sensors and actuators are usually attached in such places where the greatest amplitude of vibration can be observed. This method requires a fast non-contact sensing with the use of a scanning vibrometer, and it will be applied in this paper.

There are two fundamental steps involved in a closed-loop system. The first step is to identify a mathematical model. The second step is to use the identified model to design a controller. In this paper the parametric identification procedure has been applied to establish the model. The process of designing the controller involved making preliminary tests, whose results were used to identify the considered system. Using a selected identification method one could receive values of unknown system model parameters. They were applied in the algorithm for reducing vibration of a plate. The authors have used the controller of the nine order and the nine order ARX system model which have been generated with standard LMS algorithm from the MATLAB System Identification Toolbox. This algorithm seems to be satisfactory enough, however in more demanding applications it can be improved (Bismor, 2012). There are many classical strategies that can be used when a mathematical model is available, for instance, poles allocation and optimal control (LQR), used also by the author (Leniowska, 2006; 2008; 2009). This article shows the way of locating sensors and actuators and proposes an approach to design an effective controller for vibration suppression of a circular plate with the use of SISO tool from the Matlab software. The test stand described was based on MicroDAQ device with the real-time operating system implemented on a OMAP processor. Finally, both the simulations and experimental results of the vibration suppression obtained with the use of MFC elements are presented.

2. Characteristics of MFC elements

The MFC element can operate in two modes: they convert mechanical energy into electrical energy (sensor), or *vice versa* (actuator). MFC elements that are made of piezoceramic fibers, unlike PZT homogeneous materials and systems, are structured in a matrix made up of components of orthotropic physical properties which are closed by an external epoxy plate. Electrodes, formed on a thin Kapton foil supplied by the electric field, generate mechanical deformations.

An electrical charge proportional to the measured voltage and the capacity element is deposited on the electrodes in the sensor mode. A relatively high voltage at low levels of vibration, which allows the user to connect the sensor to the system without additional amplifiers, is the advantage of MFC components employed as the sensor. It has been used in the experiments presented in this article. Unfortunately, these elements are not suitable for static strain measurement. MFC components have a relatively high plane of contact with the object to which they are attached; they can also be characterized by a high flexibility at a low weight which is not significantly affected by changes in kinetic parameters of the test object. In comparison with other piezoelectric elements they have a greater value possible for generating a relative deformation.

MFC components have a large inner capacity and the supply voltage above 1 kV in order to provide reliable adjustment of the offset angle and vibration, especially if the user deploys a greater number of MFC components on the surface. Mutual displacement of the current and supply voltage of a value close to $\pi/2$ indicates almost purely capacitive nature of the piezoelectric elements and at the same time confirms the fact that the losses are very small and do not exceed 3–4%. The capacitance value changes in relation to the frequency and amplitude of the supply voltage (Wilkie *et al.*, 2004).

3. Construction of the test stand

A thin circular plate 1 mm thick, placed on a cast-iron cylinder with a height of 0.8 m, a diameter of 0.5 meter and a weight of about 120 kg, was the object of the research. The test plate was placed between two planes – the upper part of the body cast-iron and the cast iron ring. The ring was pressed against the disc by pneumatic cylinders, which made it possible to obtain a uniform load on the circumference of the disc. Measuring the force of the fixing ring was possible by reducing the manual valve. There are two ways to use active circuits composite:

- sticking them to the surface elements,
- creating integral whole with the object.

In the study the first method was adopted. A low frequency loudspeaker installed centrally at the bottom part of the cylinder was used as a device for forcing plate vibration. By comparison, the vibrations of the plate can also be excited by application of a MFC rectangular element M4312-P1 sized 43×12 mm, glued to the plate.

Another MFC element in the shape of a star (Fig. 1) – a combination of 8 actuators arranged in a circle with a radius of 40 mm (Star MFC) – has been used as an actuator to suppress the plate vibrations. This element has the effect of d33-forced deformation of the active component along the direction of the electric field (and the direction of polarization of the material). In practice, active elements with the effect of d31 – strain in the plane perpendicular to the running direction of the electric field – are used. With the effect of d33 there are higher elongations (2000 ppm) in comparison with the elements where the d31 effect is used (750 ppm).

Fig. 1. MFC element used as an actuator.

A piezoelectric actuator has been placed on the plate in the axially-symmetrical way, allowing for a substantial reduction in computational complexity of the problem. The SM-112 type of loudspeaker was positioned within the cylinder body. While conducting the research polyurethane foam was placed in the core between the built-in loudspeaker and the plate in order to obtain a uniform distribution of the object-induced forces.

A MFC M2807-P1 element, used as a sensor for measuring the vibration, was directly plugged into the analogue input devices for data recording. The signal coming directly from the sensor has a relatively high voltage and there is no need for an additional amplifier.

4. Measurement of the vibration – location of sensors and actuators

A laser scanning vibrometer was used to measure the vibration of the plate. The whole test stand is shown in Fig. 2.

The constructed test stand contains: 1 – the measuring head of the vibrometer, 2 – LCD monitor, 3 – CPU of the scanning vibrometer, 4 – the cylinder body with a loudspeaker inside, 5 – the plate – test object, 6 – the pneumatic cylinders controlled by the nitrogen. Vibration of the measurement points on the plate surface was used for the location of the sensors and the actuator, and then the signal from the vibration sensor was transferred to create the model using the

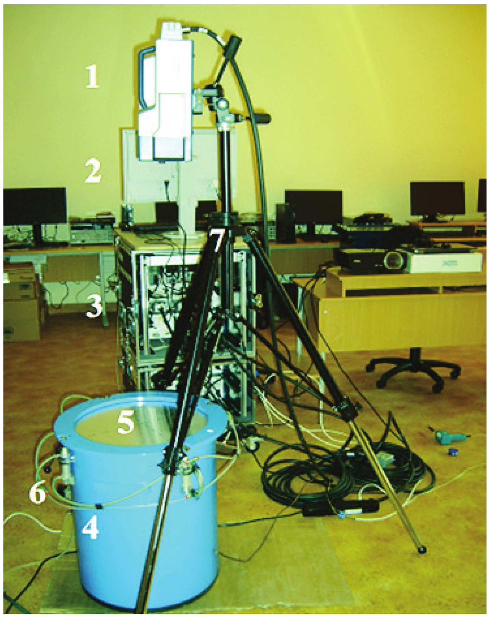

Fig. 2. Test stand with the laser vibrometer.

identification parameter procedure. Laser vibrometer measurement consists in proper configuration of the laser head, and then generating the points grid which determines where the measurements will be collected.

The number of chosen points influences the measurement accuracy, but also the time of the test. The next stage of the experiment is to scan the surface of the vibrating plate in the previously designated 193 points.

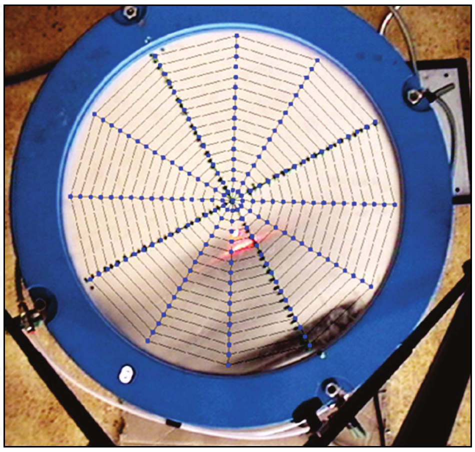

Fig. 3. Measuring grid used to test vibrations at different points.

In the conducted research both a loudspeaker and the MFC element were used to excite plate vibration with a signal of constant amplitude and variable frequency in the range from 0 to 1000 Hz. The results of the two experiments are shown below – in the form of a velocity diagram in the frequency domain for one of the points. The results for every grid point were averaged for the three measurement cycles.

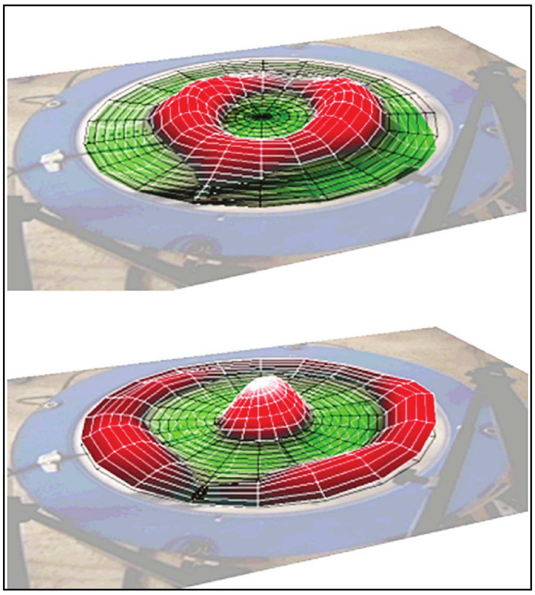
Fig. 4. Resonant mode shape.

An FFT analysis made it possible to determine the resonant frequencies of the object. The velocity component at the frequency of 190 Hz was clearly dominant, and its form is shown below. The reduction of the vibration amplitude usually occurs as a result of the control forces, respectively designated by the designed controller. It reduces the greatest amplitude of the vibration at the first resonance frequency and usually causes the reduction of other harmonics with smaller amplitudes occurring at different frequencies. For this reason, the resonance frequency of 190 Hz was taken into account in the process of designing the controller.

The location of the vibration sensor and the actuator which was designed to reduce vibration was selected experimentally, in places where the deflection of the plate had the highest value.

The actuator should be placed at a location to excite the desired modes in the most effective way. This technique can produce good results, but not necessarily the optimal solution.

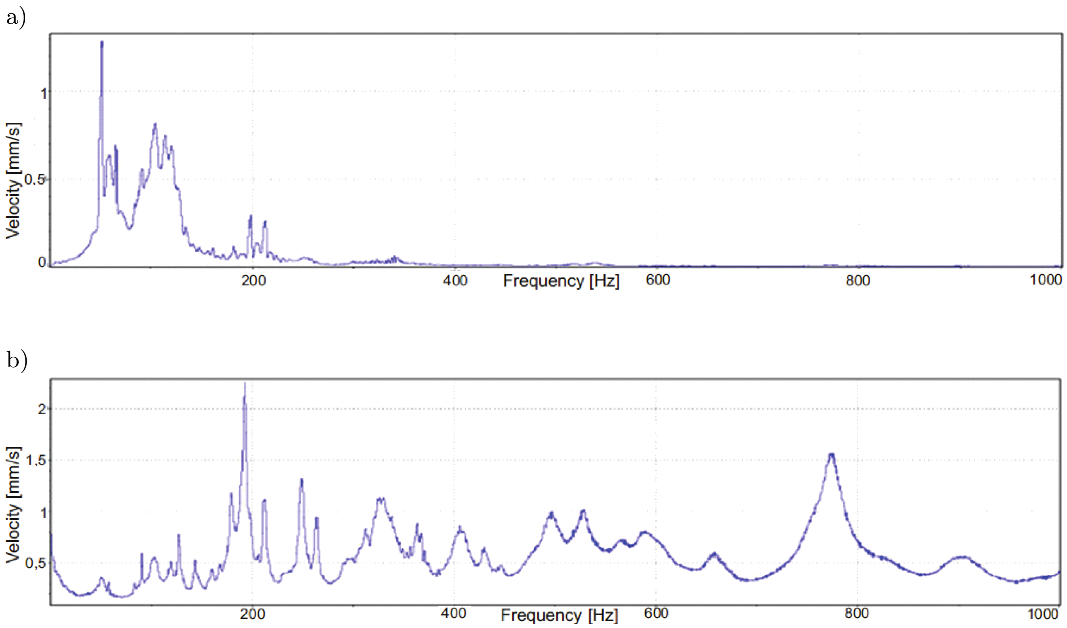

Fig. 5. Response of an object excited with the chirp signal of a frequency ranging from 0 to 1000 [Hz] with the use of: a) the loadspeaker, b) MFC actuator.

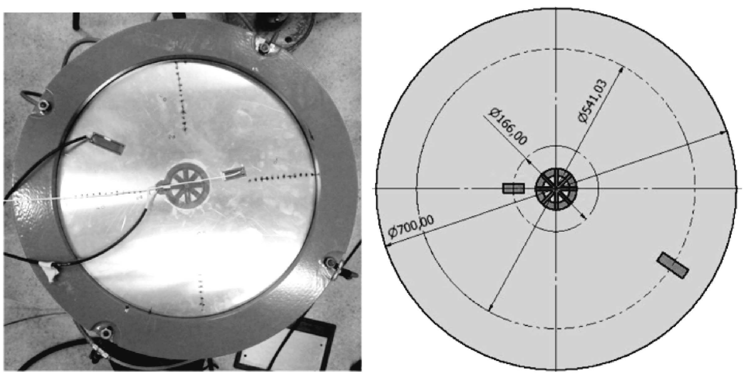

Fig. 6. Location of the sensor and actuators [4].

5. Identification of the object

Identification is the process of developing a parametric model for a physical system by use of experimental data. Assuming that the sampled signal values can be related through the linear difference equation given by Eq. (1) (SÖDERSTRÖM, STOICA, 1989):

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

where $y(k)$, $u(k)$ represent respectively the output and input at discrete time $k = 1, 2, 3, \ldots$, nA is the number of poles, nB is the number of zeros, d is the number of samples before the input affects the system output, and $e(k)$ denotes white noise.

Active vibration suppression can be generally characterised by the diagram in Fig. 7. A plant is described by the transfer function G_o, the actuator-to-error transfer path. The controller (MFC-Star) operates on the error sensor to generate actuator drive signal to reduce the plate vibration. The linear representation (1) shown above, known as an autoregressive model with exogenous input (ARX), can be rewritten using z^{-1} operator as Eq. (2):

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

where

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

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

is considered as a base model of the vibrating planar circular plate clamped at the edge. In order to obtain the polynomials coefficients in (3), (4) a linear chirp input signal is applied. The chirp signal, whose frequency inreases from 30 Hz to 500 Hz with the amplitude of 2.5 V, was generated by the MicroDAQ within 10 seconds. This signal was transferred by the analogue output to the star shaped MFC actuator. With the use of the analogue input the signal from the vibration sensor glued on a thin plate was read and archivised. The whole process was held in the sampling frequency of 10 kHz. The data from the sensor have been seen and

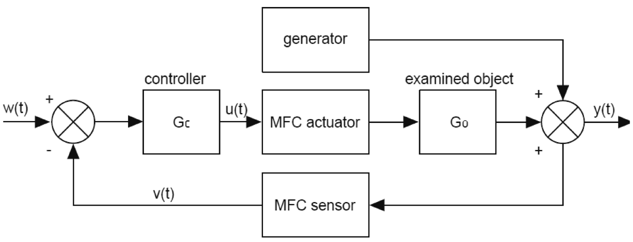

Fig. 7. Diagram of a control system.

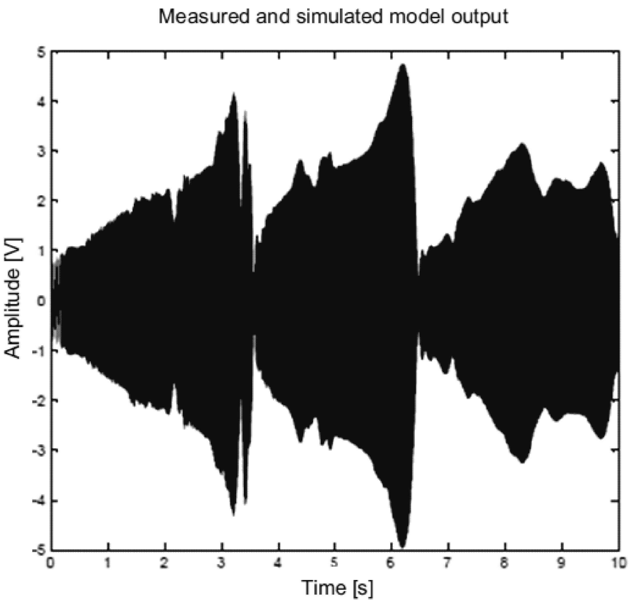

Fig. 8. Response of the object to a chirp signal.

saved on the host with the Matlab/Simulink software. In Fig. 9 we can see the response of the plate in question, driven by MFC.

An experimental method of deriving parameters for the variables in Eq. (3), (4) has been developed with the Matlab Toolbox. Many attempts have been carried out to find an appropiate model. The figure below shows a characteristic model of the third order, which is hardly capable of mapping the real object.

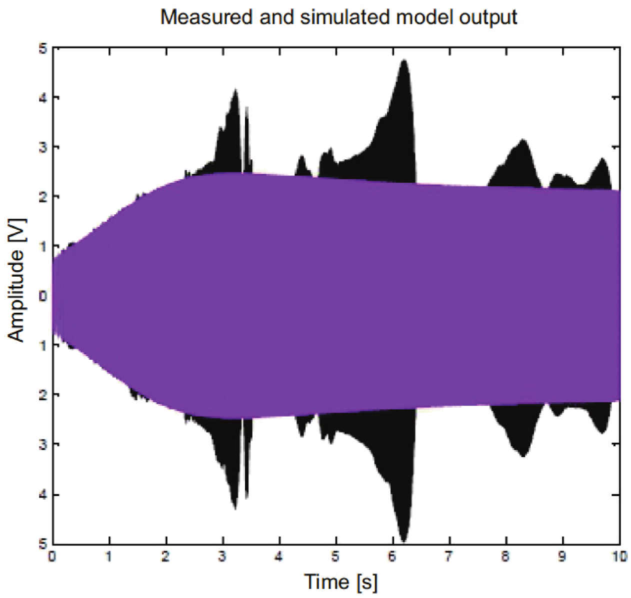

Fig. 9. Characteristics of the third order model.

The accuracy of the model derived was estimated according to the Matlab criterion of *best fits* defined as (8):

$$BEST\_FIT = (1 - |y - y_{\mathrm{model}}| / |y - \mathrm{mean}(y)|) \cdot 100\%, \tag{5}$$

where y is the measured output, y_{model} is the simulated or predicted model output, and mean(y) designed the mean of the measured output. The value of *best fits* equals 100%, if it corresponds to a perfect fit, and 0% indicates that the fit is not better than guessing the output to be a constant ($y_{\text{model}} = \text{mean}(y)$). With the Matlab Identification Toolbox many models of different orders have been calculated. In order to optimize the trade-off between quality and complexity, the ninth order model with accuracy of 83.28% was used for further studies (Fig. 10). It has the form:

$$\begin{aligned} G_o = {} & (-0.7015z^{-9} + 6.317z^{-8} - 25.39z^{-7} + 59.74z^{-6} \\ & - 90.73^{-5} + 92.22z^{-4} - 62.74z^{-3} + 27.55z^{-2} \\ & - 7.083z^{-1} + 0.8127)/(-0.8422z^{-9} + 7.608z^{-8} \\ & - 30.66z^{-7} + 72.36z^{-6} - 110.2z^{-5} + 112.3z^{-4} \\ & - 76.6z^{-3} + 33.72z^{-2} - 8.693^{-1}). \end{aligned} \tag{6}$$

Its characteristic response is shown below.

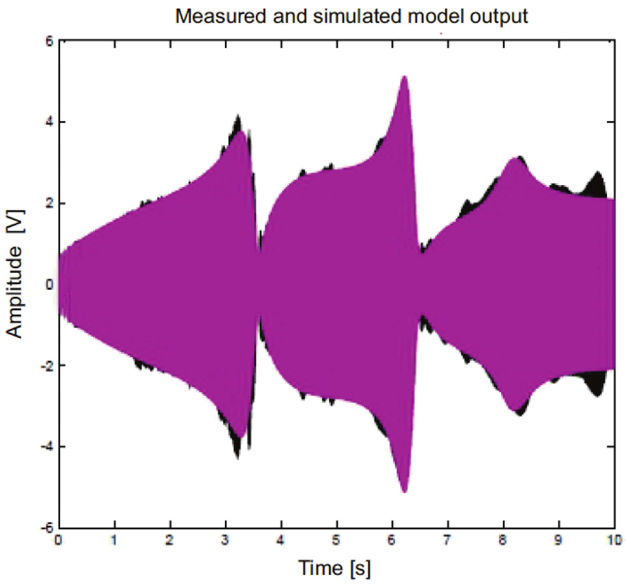

Fig. 10. Characteristics of the ninth order model.

The obtained identification model is the result of a compromise between acceptable quality and simplicity of the implementation. The implementation of the ninth order model on the MicroDAQ device was carried out successfully.

6. Controller design

A variety of control methods proved to be effective in vibration suppression. This paper presents an approach to active control using a pole placement technique. Since the MFC actuator is being used for vibration control of the plate, there is therefore a zero reference signal for the closed loop system. Having developed the transfer functions of the considered system (6), we can design a feedback control law to change the response of the system in a desired way. A requirement of closed-loop systems is that the roots of the characteristic polynomial are inside a given region of the left-hand plane.

For the object described by the ARX model (2–4) we seek a controller transfer function expressed as the ratio of polynomials $Q(z^{-1})/P(z^{-1})$, which is adjusted, so that the closed-loop system shown in Fig. 11 can fit the desired criterion (e.g. stabilizing the system and reducing its vibration).

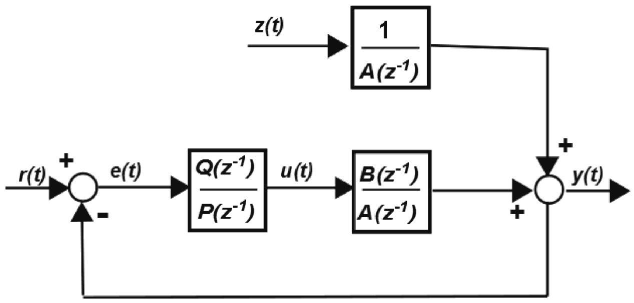

Fig. 11. Scheme of the considered closed-loop system.

We try to find a controller:

$$G_C = \frac{Q(z^{-1})}{P(z^{-1})} = \frac{q_0 + q_1 z^{-1} + ... + q_n z^{-n}}{1 + p_1 z^{-1} + ... + p_n z^{-n}}, \tag{7}$$

such that the roots of the characteristic polynomial can be placed in arbitrary locations. The degree of the controller, n, as well as the specific controller coefficients: q_0, q_1, ... q_n, and p_1, $p_{2,...}p_n$, are to be chosen with the use of *SISO Design Tool* from MATLAB.

In the *SISO Design Tool* software the controller can be designed by inserting zeros and poles – by placing them on the charts. The characteristics of the frequency can be shaped – which is necessary to ensure adjusting of the phase and gain margin. The designer does not obtain optimal settings ready right away, but he shapes the characteristics of choosing the appropriate settings. Finally, the accepted location of poles and zeros for the closed-loop system is shown in the figure below.

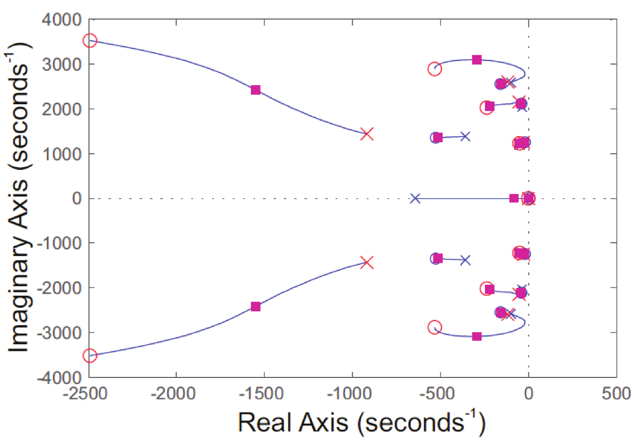

Fig. 12. Location of zeros and poles of the system.

On the basis of the designated ninth order identification model, the following controller transfer function was determined with the use of Matlab tools:

$$G_C = (1.187z^9 - 9.711z^8 + 35.5z^7 - 76.11z^6 + 105.5z^5 - 98.06z^4 + 61.15z^3 - 24.68z^2 + 5.854z - 0.6219)/(z^9 - 8.641z^8 + 33.32z^7 - 75.27z^6 + 109.7z^5 - 107.1^4 + 69.92^3 - 29.47^2 + 7.275z - 0.8014). \quad (8)$$

To examine the feasibility of the obtained controller, the attained model has been applied both in simulations and experiments.

7. Implementation of the design controller

In the developed concept of the active vibration suppression, the main element is the system control unit – MicroDAQ, which is based on SYS/BIOS, TI hard real-time operating system. MicroDAQ is a DSP real-time control measurement system designed to use in a Rapid Control Prototyping environment. Thanks to this platform there is a possibility of remote data acquisition, remote controlling and testing or measuring.

On the main board of the equipment (Fig. 13) there is an OMAP-137 processor consisting of four separate processors: advanced DSP unit responsible for the calculation, ARM processor for general purposes such as communication with the user or data archiving, and two 32bit PRU processors. MicroDAQ has 8 analogue inputs with a resolution of 16bit 500ksps sampling time, and a voltage range of +/−10 V, +/−5 V, 0–10 V, 0–5 V (programmable). The analogue inputs are protected to 25 V. The device has 16 analogue outputs with 16 bit resolutions and the voltage in the range of +/−10 V, +/−5 V, 0–10 V, 0–5 V (programmable). It is also equipped with an additional digital interfaces: PWM, ENC, UART, I2C, SPI.

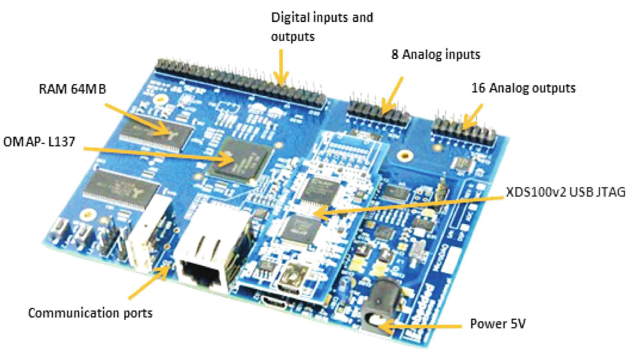

Fig. 13. Mainboard of MicroDAQ [17].

The described device was used to read the data from the vibration sensor and to control the operation of the actuator. Using Embedded Coder target for MicroDAQ it is possible to build application from Simulink model, upload it on MicroDAQ device and run it in as a standalone application.

8. The results of the simulation and the experiment

In the Simulink environment the vibration reduction system was built with the use of the obtained closed loop control‘ (7). This system was used to simulate the operation of the controller. The figures below show the results of simulations of the designed control procedure with the use of the STC controller of the 9th order, for different input signals, obtained with the Simulink/Matlab computer program. To examine the effect of the controller on plate vibration suppression, the model was first subjected to a sinusoidal signal with a constant amplitude and frequency of 190 Hz and subsquently to a chirp signal of 0–1000 Hz.

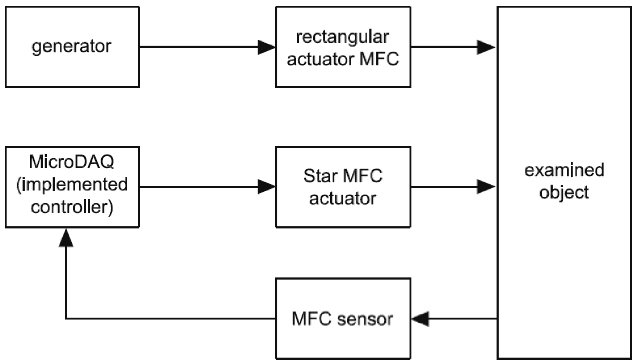

Fig. 14. Vibration reduction system used during the simulation controller operation.

The simulation takes place in two stages. In the first stage, the excitation signal was a sine wave of the frequency of 190 Hz. After 2 seconds the controller was turned on. The plate responce is presented below. The graph shows a significant reduction of the sinusoidal signal after two seconds. The plate vibrations have been reduced by about 90%.

The second excitation signal was a linear chirp waveform of the frequency range from 30 Hz to 500 Hz. After 2 s the regulator was turned on and the plate response was also reduced. The reduction of the plate vibration is not as good as for the previous sin waveform, some higher harmonics have not been suppresed well. The output signal is presented below.

After the simulation, the vibration reduction system was built, which was then implemented on a device with a real-time system.

During the real measurement a sine signal of the resonance frequency of 190 Hz was used. The MFC sensor signal during the real test is presented below. After 2s the controller was turned on and the plate response was reduced by about 50%.

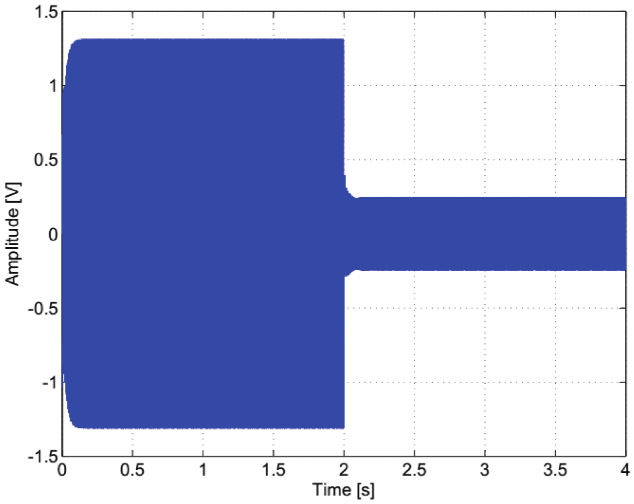

Fig. 15. Plate response for 190 Hz periodic excitation; 0–2 s open loop control system, 2–4 s close loop control system.

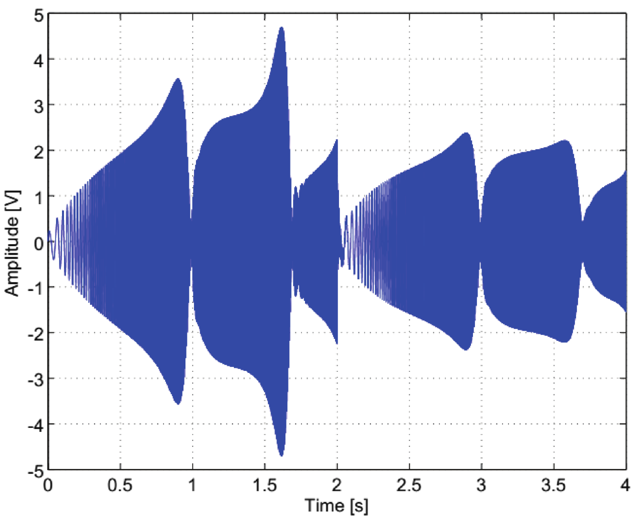

Fig. 16. Plate response for the linear chirp signal excitation; 0–2 s open loop control system, 2–4 s close loop control system.

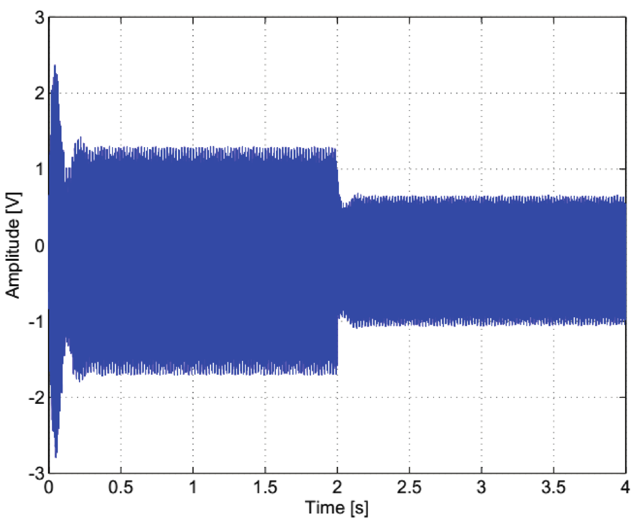

Fig. 17. Experimental results – the plate response for sinusoidal excitation of 190 Hz; (0–2 s) without control; (2–4 s) with control.

Next, the object was excited by a chirp signal of the constant amplitude and frequency ranged from 30 to 500 Hz in order to see how the controller was able to suppress the vibration of different frequencies. The output signal is shown below (Fig. 18). It can be seen that in a real test the controller reduced almost all frequences, better than in the simulation.

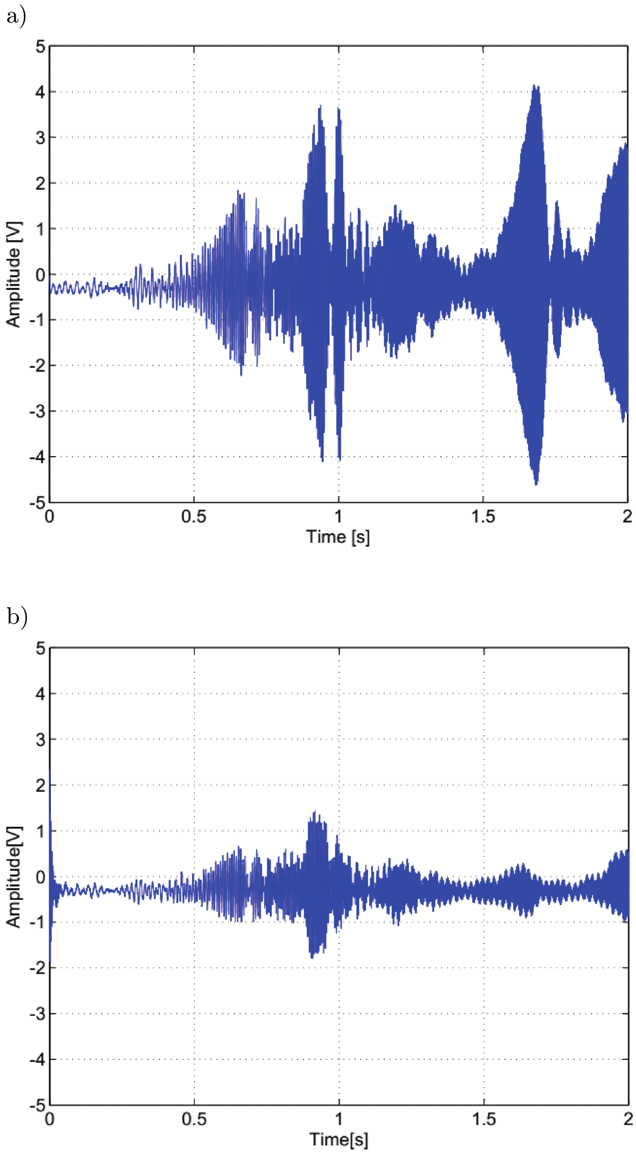

Fig. 18. Experimental results – the plate response for chirp signal (from 10 Hz to 500 Hz) excitation; a) open loop control system, b) close loop control system.

9. Summary

The aim of this work was to investigate the feasibility of using MFC actuators to suppress circular plate vibrations. The article shows the way of choosing the location of the sensors and the actuators with the use of a laser vibrometer and proposes an approach to design an effective controller for vibration suppression of a circular plate. The described test stand is based on a MicroDAQ device with a real-time operating system implemented at the TI OMAP137 processor, which includes DSP and ARM cores. The feedback control is realised via a circular MFC star-shaped element glued to the central part of the plate. The mathematical model of the object was determined with the use of the parametric identification method. Next, this model was used to design a pole-placement controller for the experimental system. The results of the simulation and tests for a real system confirmed the effectiveness of this method in vibration reduction. Active vibration control based on the developed algorithm is proved to be effective by experiments for reduction of a single and multi-frequency disturbance (chirp signal) acting on a circular plate.

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