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Application of a fuzzy PI controller in regulation of active piezoelectric composite structure

Abstract. *The paper presents results of damping resonant vibrations of a beam with the embedded macro fibre composite (MFC) piezoelectric element. Fuzzy PI linear and nonlinear algorithms were applied during the tests. The initial laboratory tests were aided by calculations and simulations performed using the Matlab software. All the experiments were managed by the DSP system built based on the 64bit TMS320C6455 board controller.*

Streszczenie. *W artykule przedstawiono wyniki badań tłumienia drgań rezonansowych belki z wbudowanym aktuatorem piezoelektrycznym typu MFC. Podczas badań zastosowano liniowy i nieliniowy algorytm rozmyty PI. Prace zrealizowano w oparciu o badania laboratoryjne wspomagane obliczeniami i symulacjami w programie Matlab. Eksperymentami zarządzał układ μP zbudowany w oparciu o platformę 64 bitowego procesora DSP typu TMS320C6455. (**Zastosowanie sterowania rozmytego PI do regulacji piezoelektrycznej struktury kompozytowej**).*

Keywords: PI fuzzy controller, suppression of vibrations, piezoelectric actuator.
Słowa kluczowe: rozmyty regulator PI, tłumienie drgań, piezoelektryczny aktuator.

Introduction

Vibrations are a parasitic phenomenon, which accompanies the essential work of different devices. The existence of these vibrations has a negative effect on the quality and efficiency of work, and leads to the reduction of reliability. There are several methods to prevent vibrations, which include:

- designing the system in a way that its work doesn't take place near the self resonant frequency of the system,
- incorporation of passive dampers which reduce vibration by increasing the viscous friction,
- application of active damping systems.

The latter represents one of the most modern approaches and offers a wide range of applications. Depending on the active element used, it can be controlled electrically, magnetically, hydraulically, etc..

This paper describes the use of piezoelectric actuator for vibration damping of a beam. Taking into consideration requirements for generation of large deformations, a Macro Fiber Composite (MFC) is used [4]. This composite system has a layered structure, where its inner layer, made of piezoelectric fibers, allows for high bending strength and large deformation. These systems can be embedded into the structure of the device, resulting in the uniform shape of the surface.

The application of the electric current-regulated MFC actuators enables to adjust the mechanical properties, change shape, and regulate movement of active components. The MFC elements belong to a group of actuators which can be used either in position control or oscillation reduction. Such systems require operation in closed loop control systems, where the type of control algorithms implemented plays a key role. However, the most popular PI controllers don't satisfy difficult operational conditions, especially when parameters of the system under control are changing. In these cases, it is required to apply controllers with better properties. A good example of such controllers are Fuzzy controllers.

This paper describes a fuzzy controller based on Mamdani models design. The results of this work allow to evaluate the usefulness of fuzzy control systems for active regulation of piezoelectric composite systems.

The research conducted in this project was aided by computer simulation methods. The results obtained through calculations made it possible to narrow the range of desired solutions which meet the conditions of the work. The laboratory tests help to determine the effectiveness of the studied fuzzy algorithm during vibration damping of the tested beam.

Laboratory setup

The laboratory setup consists of a carbon composite beam that is mounted at the support and excited by an electromagnetic shaker (Fig.1). The MFC actuator and strain gauge are embedded onto the beam in optimally selected positions resulting in the most effective operation. The beam dimension and measured kinetic parameters were as follows:

- length, width and thickness: 300 mm x 13 mm x 2.2 mm,
- self resonant frequency f_r = 27.7Hz, ω_r = 174.04 rad/s,
- viscous damping coefficient γ = 2.5.

Taking into account these parameters, a sampling time of measured and controlled quantities has been chosen as 50μs. To ensure the required bending strength, the Macro Fiber Composite MFC M-8503-P1 actuator has been applied. Its required supply voltage U_{smax} is in the range (-500V ÷ 1500V).

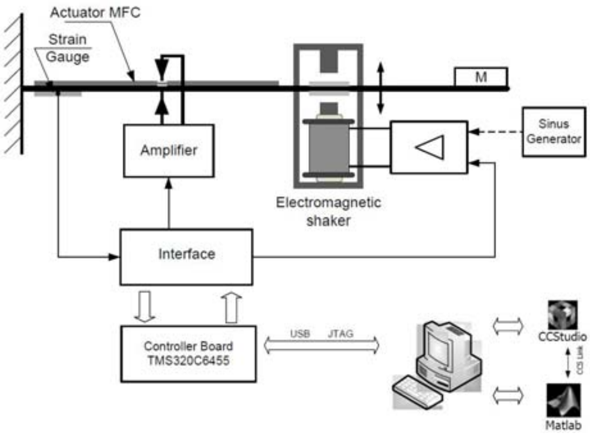


Fig.1. The laboratory system equipped with: MFC actuator, supply amplifier, DSP controller board, PC system, digital and analog interfaces, shaker and other equipment.

The control system was built upon the 64-bit TMS320C6455 Digital Signal Processor supported by a PC system. This DSP-based setup allowed to execute control algorithms transformed to C-code which were then implemented in real-time in the physical model. The Controller Board was equipped with peripherals such as gauge bridge, current and voltage sensors.

Communication with a PC was provided by JTAG, USB interfaces. The Code Composer Studio board software enables real time data exchange between the DSP controller and the Matlab program executed on the PC computer.

The principal simulation and laboratory studies were preceded by the identification tests of the parameters of the beam with embedded MFC actuator [2]. These parameters constituted the input data for further simulations and laboratory tests.

Damping of the beam oscillations in the presence of periodic distortion is considered the main task of the control system. According to the structure of the laboratory system, the value measured by strain gauge bridge constituted a feedback signal in a control loop system (Fig.2).

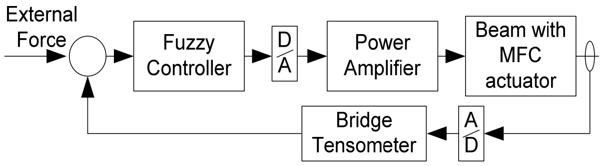


Fig.2. Diagram of the feedback control system

During the tests the setpoint of deformation was taken as equal zero.

Simulation research

The simulation model reflects the operations of our laboratory setup. All components of the computational model have their equivalents so that the results of simulation studies can be used for laboratory experiments.

Vibrations of the beam with its end free are described by nonlinear partial differential equation (1) [3, 4]. The dimensionless variable x corresponds to a displacement of the free end to the beam length.

$$(1)\ \ddot{x} + 2\gamma\omega\dot{x} + \omega^2 x + \beta x^3 - \delta\left(x\dot{x}^2 + x^2\ddot{x}\right) = A_m \sin\left(\Omega_m t\right)$$

where:

ω – the self resonant frequency of the tested beam with embedded MFC actuator,
γ – viscosity coefficient,
β – coefficient of nonlinear component,
A_m – amplitude of external force,
Ω_m – frequency of external force.

A typical structure taken into consideration during the studies was a structure of the fuzzy PI controller with amplifier and integration tracks, and fuzzification, inference machine and deffuzification (Fig.3) [5].

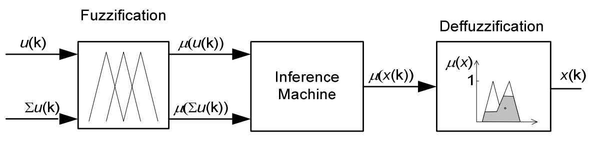


Fig.3. Function blocs of Mamdani PI Fuzzy Corrector

The beam simulation model based on eq.(1) was designed using function block **Fnc** from the Simulink library User Defined Function (Fig.4). **Mux** block operates as a bus creator, which collects variable *x*(*k*) and its first and second derivatives.

During controller implementation, the Mamdani algorithm, operating on fuzzy input and output sets, was selected. During the design, the following rules were implemented:

- since metric input space includes measured and system variables, the saturation effect is not allowed,
- input membership functions have triangle or gamma shapes,
- the inference machine gives results corresponding to the typical conclusions involving fuzzy sets, and operates according to the PI rules,
- based on preliminary tests, center of gravity method was chosen as a deffuzification function.

This study was conducted for two sets of membership functions corresponding to the linear (Fig.5a) and nonlinear (Fig.5b) algorithms.

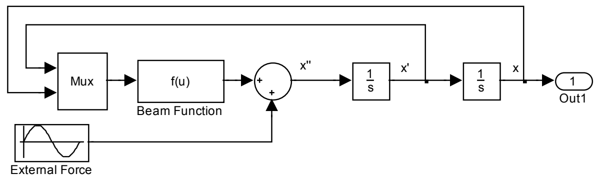
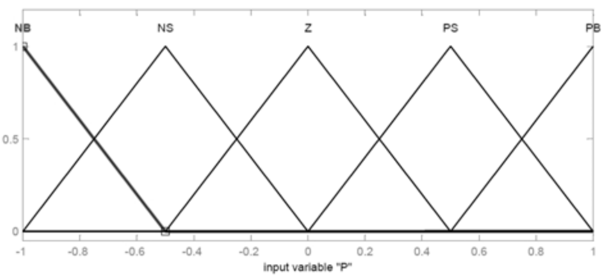


Fig.4. Simulink model of the beam with nonlinearities described in Beam Function block

a)



b)

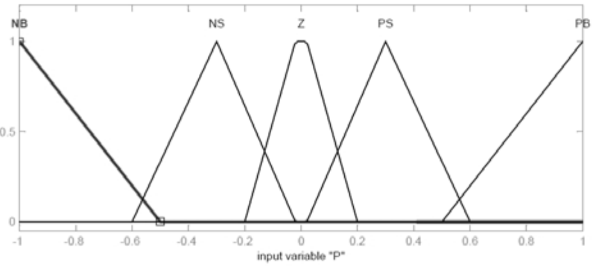


Fig.5. Membership input functions for a) linear Fuzzy PI Controller; b) nonlinear Fuzzy PI Controller

Fife argument base rules are the same for both sets. Its dependencies are shown in Table 1.

Table 1. Inference machine of PI fuzzy corrector

	NB	NS	Z	PS	PB
NB	NB	NM	NS	NL	Z
NS	NM	NS	NL	Z	PL
Z	NS	NL	Z	PL	PS
PS	NL	Z	PL	PS	PM
PB	Z	PL	PS	PM	PB

where,
NB – negative big, NS – negative small, Z – zero, PS – positive small, PB – positive big.

Membership functions, inference rules and deffuzification method described in this work gave satisfactory damping results. The results of simulation tests were nearly identical to the laboratory results. The highest standard error, 10% was seen only during the first moments after switching on the controller and it was equal.

Description of laboratory tests

At the time of activation, the beam was in a steady state, oscillating at a resonance frequency. After switching on the controller (*t*=2sec.), transient state arised, lasting less than 1 sec. At that time, the amplitude of the beam repeatedly decreased giving less than 13.5% of initial value (Fig.6a).

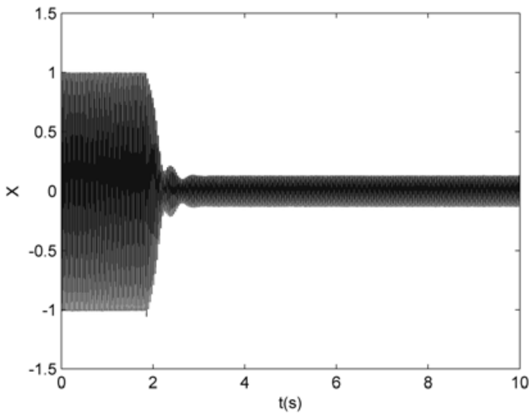


Fig.6a. Mechanical damping of the beam by MFC control system with linear Fuzzy PI controller

In the initial period of controller operation, the demand value of supply voltage rapidly increased at MFC terminals. Its maximal value reached up to 500V. However, after stabilizing output value, voltage at MFC terminals decreased to about 82 V (Fig.6b).

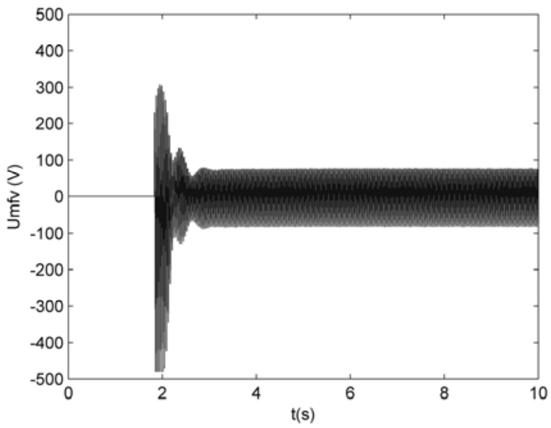


Fig.6b. Output of voltage amplifier at the MFC terminals

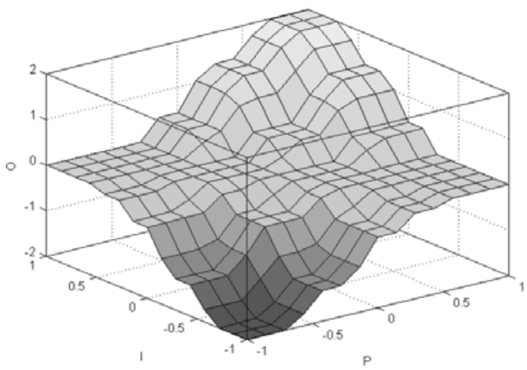


Fig.7. Control surface of nonlinear Fuzzy PI controller

Slightly different result was obtained after the application of nonlinear controller. Shifting the intersection of membership functions ***μ*** outside the value of 0.5 changed the sensitivity of the controller. For example, the extension of membership function NB increases dominance of this function in relation to neighbor functions. This property is especially important in cases of large amplitude deformations, when a limitation of integrator with respect to proportional action is required. As a result of those changes, the control plane is going to change the shape of a uniform surface into a form with different speeds of operation (Fig.7).

The results of application of nonlinear controller that are consistent with the membership function (drawn in the Fig. 4b) and the inference machine (written in Table 1) are shown in Fig.8.

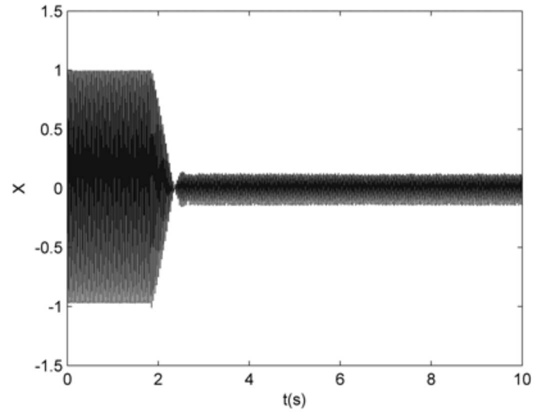


Fig.8. Mechanical damping of the beam by MFC control system with nonlinear Fuzzy PI controller

Comparing the performance of both controllers, the final result of damping was at the same level, as seen in Figs.6a and 8. The amplitude of vibrations remains the same for both algorithms. The differences are visible only in a short time period, after switching on the control system. In these initial moments, the system operates still with large amplitudes of vibration. It means that for large amplitudes, the nonlinear effects described by γ, β and δ coefficients (1) have greater impact on transient states. In contrast, for small amplitudes, the model can be explained in a linear fashion, that is why the linear algorithm is more appropriate.

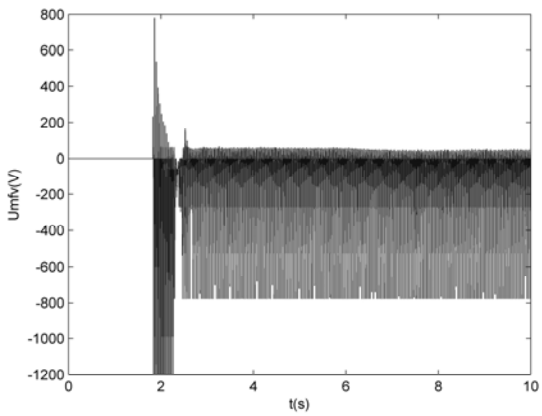


Fig.9. High voltage amplifier output (MFC)

The work of nonlinear corrector generates, as a side effect, pulses with amplitude higher than for linear algorithm. For the nonlinear controller these pulses increased up to -1200V at transient states and up to -800V in harmonic steady state. This is particularly unfavorable for steady state, where amplitude increased nearly ten times in comparison to linear harmonic, while damping efficiency remained at the same level.

The effect of corrector amplification on the dumping effectiveness

Additional series of tests were performed for various proportional coefficients. Vibration levels were studied in steady state for a system with the controller switched on. The significant effect of gain factor on damping level was observed, especially in the range of 0 to 1 (Fig. 10). The increase in value of the amplifier factor is making the system more sensitive to existing errors. This has a positive effect in steady state, but it may bring unexpected extension of a transitional period.

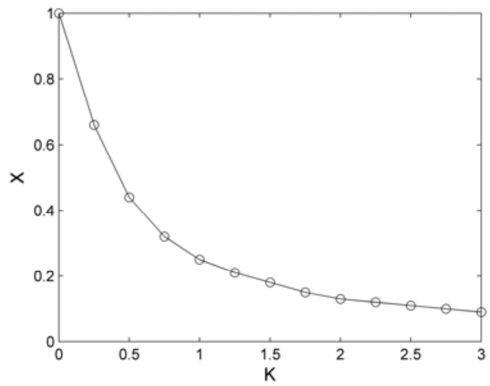


Fig.10. Experimental results of damping vibration with resonant controller: K – amplifier coefficient of PI controller, X – dimensionless amplitude of vibrations

Fig. 11 demonstrates that the nonlinearity of the beam is visible when forcing frequency is beyond the self resonant frequency of the beam ω_r (Fig.11). For an open loop system, vibrations are the highest at the resonant frequency. Beyond that point, the amplitude of vibrations decreases, but at different velocities on both sides of ω_r. For a closed loop system, the level of vibrations stays nearly the same regardless of the forcing frequency. However, in some cases, in a closed loop system with PI, linear corrector causes an increase of vibration when compared to an open loop system.

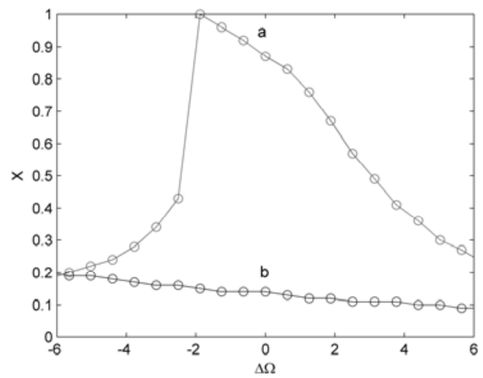


Fig.11. Mechanical damping of the beam by MFC control system with Fuzzy PI controller: *ΔΩ* – detuning of the own frequency, *X* – amplitude of the beam vibrations (dimensionless), *a* – open loop, *b* – PI fuzzy linear controller (closed loop)

Therefore, the effectiveness of a PI controller decreases significantly beyond the resonant frequency. Consequently, suppressing vibration with application of PI controller beyond a certain range around ω_r is not justified.

Final conclusions

Based on our results, the conclusions of present stage of research can be formulated as follows:

- at steady state, the effectiveness of resonant vibration damping is nearly the same for both fuzzy controllers, linear and nonlinear, and depends on amplifier coefficient to a significant extent,
- the duration of the transient state with nonlinear corrector is shorter than the regulation time for the linear corrector,
- the voltage supply for a nonlinear corrector is larger than for linear one,
- the advantage of the application of PI fuzzy controllers to damping vibrations exists only in the range around the self resonant frequency of the beam.

Additional problems related to the utilization of fuzzy PI controllers may involve optimal nonlinear tuning of the controller and determining energy efficiency of the system. Explanation of those issues will be presented in further publications of the authors.

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