DESIGN AND COMPUTER MODELLING OF SMART COMPOSITE MATERIALS OF THE TYPE LAMINATED METAL-CERAMIC COMPOSITES WITH NEURAL NETWORK ADAPTIVE CONTROL OF ELASTIC WAVES TRANSFORMATIONS

V. D. Koshur

Institute of Computational Modelling of RAS
660036, Krasnoyarsk, Academgorodok, RUSSIA

SUMMARY: The converse piezoelectric effect is used to suppress the amplitudes or to modify the frequency of elastic waves which propagated along thickness of a laminated metal-ceramic plate when on the face surface of a plate is applied the oscillating pressure. The control problems involve the minimisation of quadratic cost functional depending on the velocity of vibration of the back surface of the plate and functional depending on the displacement of the back surface by using the adjustment of the neural network with the input signals as the voltages of sensors piezoelectric layers and the output signals as voltages applied to the actuators ceramic layers. The presented results are concerned with computer simulation of the proposed animated composite materials as joint mechanic, neural network and electronic system which has been named as the Matrix Electronic Materials (MEM). The results of modelling of elastic waves transformations have been shown an ability of MEM to suppress on the order the amplitudes of oscillations.

KEYWORDS: smart materials, computer modelling, neural network control, laminated metal-ceramic plate, elastic waves transformation, suppression of oscillations.

INTRODUCTION

A structure or material with embedded sensors and actuators which has controlling connections is like a living organism and is named as smart structure or material. One of the new directions in the active control of structures involves the application of piezoelectric sensors and actuators using the direct and converse piezoelectric effects to induce control action and it may be used for example for noise or vibration suppression [1-4]. Recently, artificial neural networks has various applications and in particular it may be used for realization adaptive control in mechanical systems [5].

The Matrix Electronic Materials (MEM) [6] can be defined as the combined active system with adaptive neural network control in the form

$$S_{MEM} = [[[[M], E], NN], G],$$

where:

- M is structural composite material with embedded sensors and actuators which possess piezoelectric properties,
- E is matrix electronic circuit for producing the interactions between sensors and actuators,
- NN is neural network for realisation the required adaptive control of system,
- G is an energy bloc or a power station for active energetic intervention,
- [...] - the brackets are extracted the different levels of connections of subsystems.

The computer simulation of the reduced system S^0_{MEM} = [[M], NN] for laminated metal-ceramics composites is developed on the based of the Discrete Variation Method (DVM) [7-9], modelling of the layered neural networks [10], using linear piezoelectric equations [11] and solution of the problems of optimal control for dynamic systems [12].

The present study is concerned with the active neural network control of the elastic waves transformations in laminated metal-ceramic plate along its thickness. The first problem is to damp the waves amplitude on the back surface of a plate when on the face surface of a plate is applied the oscillating pressure. The second problem is to reduce the frequency of oscillating displacement of the back surface of a plate to a given value. These problems are solved as minimisation cost functional for the dynamic mechanic-electronic system by using the adjusting weights of synapse map of the neural network in the form of the three-layered network. The input signals of neural network are the voltages of the sensors layers of a plate and the output signals are the voltages for actuators layers of a plate.

BODY OF THE PAPER

Assumptions and Equations

We consider a layered plate with thickness H along coordinate axis z and parallel layers to coordinate axis x, y with thickness h_α , α=1,...,k (k is the number of layers) and alternating layers of aluminium (A) and ceramic (C). For numerical example will be used the structure of laminated metal-ceramic plate in the form

$$F(t) \rightarrow [A+C_1^0+A+C_2+A+C_3^0+A+C_4+A+C_5^0+A+C_6+A]$$

here k=13, C_i^0 for i=1,3,5 are the sensors layers and C_i for i=2,4,6 are the actuators layers (the thickness of every layer h=1mm), symbol "+" is denoted the isolated glued connection of layers with electrodes on the boundaries of ceramic layers, $F(t) = F_0\sin(\omega t)$ is the external pressure ($\omega=5\pi\bullet10^6$ 1/s, $F_0=10^5$Pa) applied on the face surface of the plate, the back surface of the plate is free.

The governing equations for the laminated plate and simplifications are derived on the basis of the following assumptions:

(i) the problem is geometrically and physically linear,

(ii) in the plane of coordinate x, y the plate has a big enough length and width, so we can neglected of the affect of the boundary condition on the contour of the plate and to assume that the vector of displacement $\mathbf{u}=(u_x, u_y, u_z)$ has component $u_x=0$, $u_y=0$ and $u_z=u(z,t)$ is the function only coordinate z and time t and we have one-dimensional dynamic deformation along coordinate z ($\varepsilon_z=\varepsilon=\partial u/\partial z$), and the vector of velocity has nonzero component $v_z=v(z,t)=du/dt$,

(iii) ceramic layers are orthotropic piezoelectric of class mm2 with z as the axis of symmetry,

(iv) the vector of electric displacement **D** and the electric field intensity vector **E** have nonzero component $D_z=D$ and $E_z=E$.

Under the above assumptions and using the DVM [7] we can obtain the discrete equations of motion for the nodal masses m_j of the one-dimensional discrete elements of the plate

$$m_j\, dv_j/dt = \sigma_{j+1/2} - \sigma_{j-1/2}\ , \ (j=1,...,s) \tag{1}$$

here $\sigma_{j+1/2}$ is the stress in the element with the nodes j and j+1. For modelling of the waves propagation in every layer has been used ten elements. From the boundary conditions for stress at the face surface we have j=1, $\sigma_{1\text{-}1/2} = F(t)$ and for back surface we have j=s, $\sigma_{s+1/2} = 0$. For the stress in the discrete elements of aluminium the elastic low gives

$$\sigma_{j+1/2} = \lambda^* \varepsilon_{j+1/2} \tag{2}$$

were λ^* is the elastic constant, $\varepsilon_{j+1/2} = (u_{j+1} - u_{j-1})/(z^0_{j+1} - z^0_j)$ is the deformation of the element with the nodes j and j+1 . For the discrete element of ceramic it follows that [11]

$$E_{j+1/2} = \beta\, D_{j+1/2} - \eta\, \varepsilon_{j+1/2}\ , \tag{3}$$

$$\sigma_{j+1/2} = \lambda\, \varepsilon_{j+1/2} - \eta\, D_{j+1/2}\ , \tag{4}$$

were λ, η, β are the piezoelectric constants (for numerical results $\lambda = 1.77 \bullet 10^{11}$ Pa, $\eta = 4.77 \bullet 10^8$ V/m, $\beta = 4.45 \bullet 10^8$ m/F [11]). For every ceramic layer with number α we have

$$\operatorname{div} \mathbf{D}_\alpha = 0\ , \tag{5}$$

$$E_\alpha = -\, \partial\varphi_\alpha/\partial z\ , \tag{6}$$

were φ_α is the electric potential for ceramic layer. From Eqn 5 in our case it follows that $\partial D_\alpha/\partial z = 0$ or for every element of the ceramic layer it follows that $D_{j+1/2} = D_\alpha$ where D_α is the function of time t only. The voltage $V_\alpha(t)$ for sensor layer with coordinate $z\in[z^0_{\alpha1}, z^0_{\alpha2}]$ is defined from Eqn 3 and Eqn 6 in the form

$$V_\alpha(t) = \varphi_{\alpha2} - \varphi_{\alpha1} = -\int_{z^0_{\alpha1}}^{z^0_{\alpha2}} E_\alpha\, dz = \eta\, (u_{\alpha2} - u_{\alpha1}) - \beta\, D_\alpha\, (z^0_{\alpha2} - z^0_{\alpha1})\ , \tag{7}$$

here $u_{\alpha1}$, $u_{\alpha2}$ are the displacements at the boundaries of ceramic layer with number α. For the actuator layer with the given voltage $V_\alpha(t)$ the electric displacement D_α is calculated from the following equation

$$D_\alpha = [\eta\, (u_{\alpha2} - u_{\alpha1}) - V_\alpha(t)] \,/\, [\beta\, (z^0_{\alpha2} - z^0_{\alpha1})]\ . \tag{8}$$

The values of the voltages for actuators $\mathbf{V^{out}}$ **=** ($V2$,V_4 ,V_6) (here in diapason [-50, +50] volt) are generated by using three-layered artificial neural network [10] with the input values of the voltages for sensors $\mathbf{V^{in}}$ = (V_1 ,V_3 ,V_5). The first layer of the network has three neurons and nine weight parameters, the second layer is as the first, and the third layer has four neurons and twelve weight parameters (the third layer has the additional constant input signal). The neuron function has been chosen in the form [10]

$$\psi(x) = x / (c + |x|),\ c = 0.2 \tag{9}$$

Thus the connection of the sensors and the actuators may be given as the neural network vector function

$$\mathbf{V^{out}} = \mathbf{F_{NN}(V^{in}, W)}\ , \tag{10}$$

were **W** is the vector of weight parameters of synapse map (30 parameters for given system). If the all parameters are defined the modelling of the dynamic system is performed by using the explicit central-difference scheme with respect to time t for a small step Δt which is adjusted to the scheme stability.

Control and Cost Functional

Let it needs to suppress the oscillation on the back surface of the plate or to damp the amplitudes of the displacement and the velocity during the elastic waves are propagated along the thickness of the plate. For this case me can defined the cost functional in the form

$$J_1 = (1/T)\int_0^T (v_s)^2 dt, \tag{11}$$

where T is the time of double running elastic perturbations along thickness of the laminated composite plate, v_s is the velocity of vibration of the plate back surface.

For the second problem it needs to transform the frequency of the displacement on the back surface to a given value ω^{opt} ($\omega^{opt} = \omega/3$) so that the required displacement is defined as $u_s^{opt}=f(t,\omega^{opt})$. For this case me can defined the cost functional in the form

$$J_2 = (1/T)(\int_0^T (u_s-u_s^{opt})^2 dt)^{1/2}, \tag{12}$$

here u_s is the displacement of the back surface of the metal-ceramic plate.

Solution of the control problems are presented as learning neural network or an adjustment the weight parameters of synapse map for minimisation of the functional $J_1(\mathbf{W})$ and $J_2(\mathbf{W})$.

Numerical Results

By integrating the dynamic system Eqn 1 (for s=131 nodal masses) with respect time t in the interval [0, T] and using Eqns 2, 3, 4, 7, 8, 10 the values of the functional $J_1(\mathbf{W})$ and $J_2(\mathbf{W})$ are computed. For minimisation of the functional $J_1(\mathbf{W})$ and $J_2(\mathbf{W})$ have been used the Hook-Jives algorithm as not required the calculation of the cost function gradients.

The graphic illustrations for the numerical results are shown in Fig. 1 - Fig. 5.

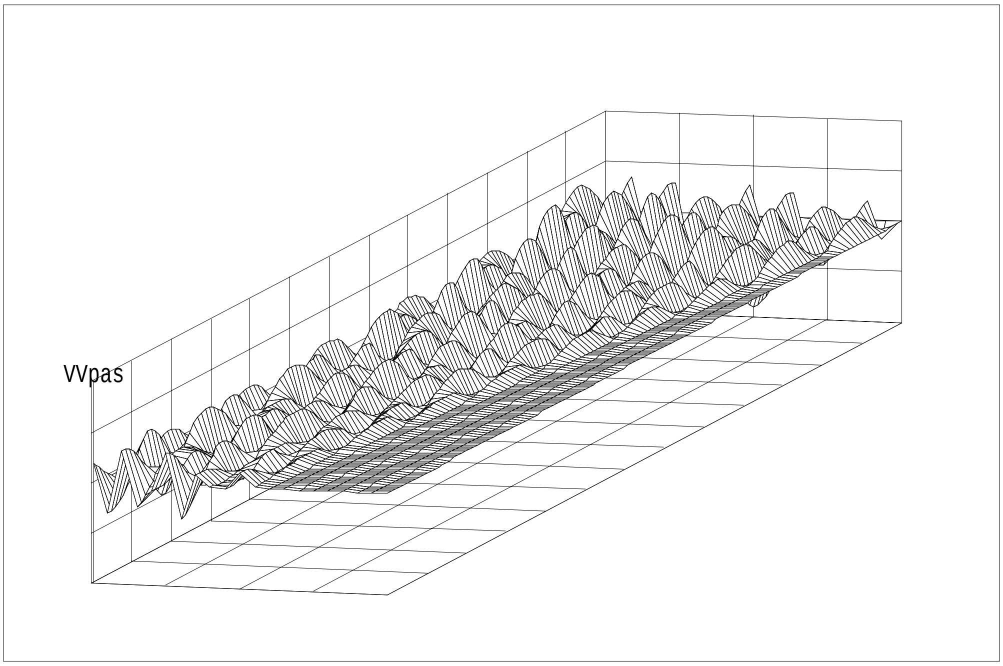

Fig. 1: The velocity distribution along thickness and time for passive dynamic deformation.

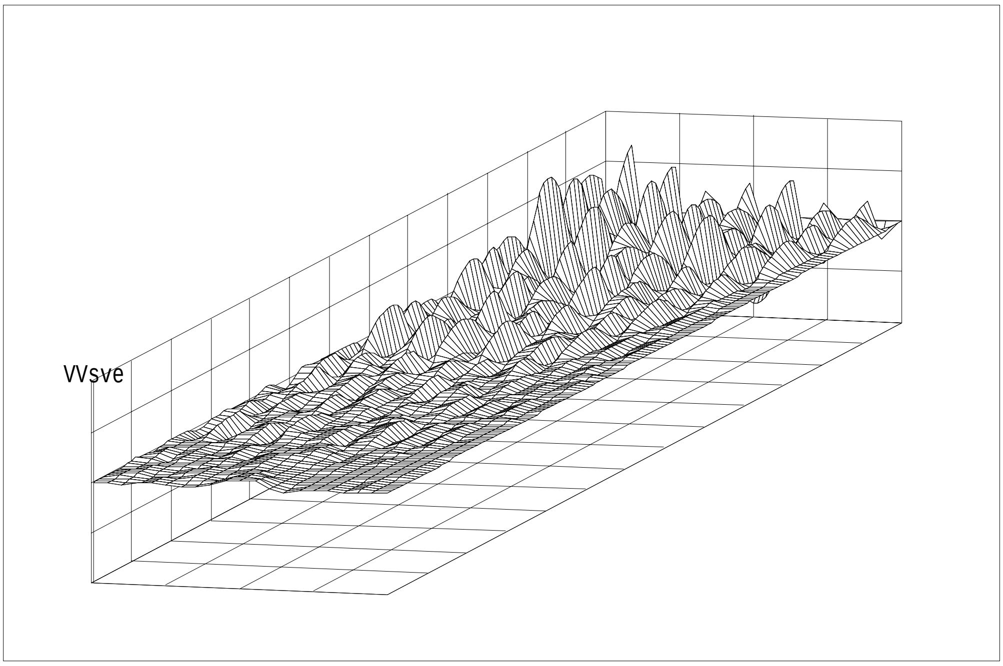

Fig. 2: The velocity distribution along thickness and time for the obtained neural network control with $J_1 \rightarrow min$.

The deformation process without control when every ceramic layer is passive we use as the base. For passive process of dynamic deformation the distribution of the velocity v(z, t) along thickness of the plate and time t as the surface VVpas with horizontal axis z, t and vertical axis v(z, t) is shown in Fig. 1. The nearest vertical cross-section in Fig. 1 is presented the coordinate z^0_{131} = 13mm with time t in microsecond which increases form the right to the left.

The level zero corresponds to the nonperturbed state of the laminated metal-ceramic plate during dynamic process of deformation. Fig. 2 shows the distribution of the velocity v(z, t) along thickness of the plate and time t as the surface VVsve for the obtained active neural network control with $J_1 \to min$. During minimisation J_1 the amplitude of velocity v_s and displacement u_s have been suppressed on the order (shown in Fig.3 and Fig.4).

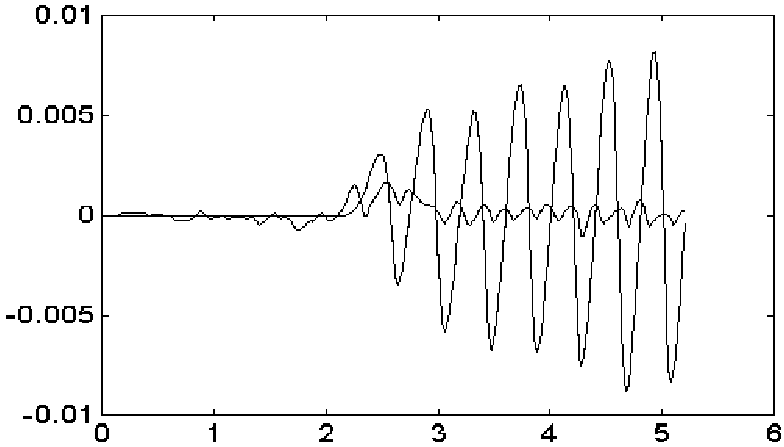

Fig. 3: Two combined graphics $v_s(t)$ - the velocity without control and $v_s^*(t)$ - the velocity for the obtained neural network control with $J_1 \to min$, horizontal axis is time t (μs).

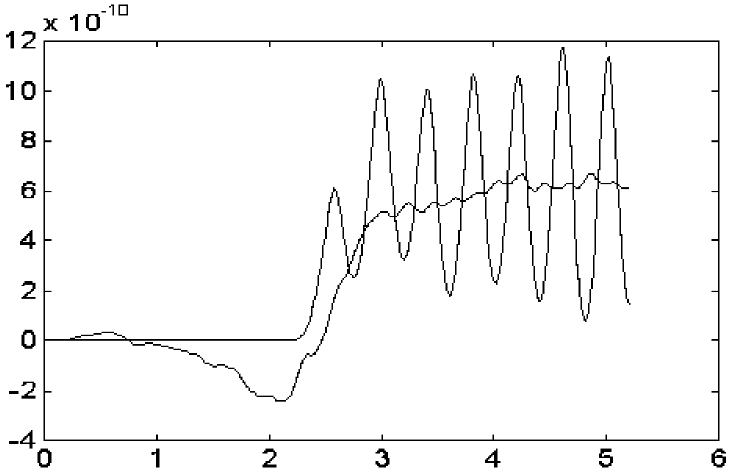

Fig. 4: Two combined graphics $u_s(t)$ - the displacement without control and $u_s^*(t)$ - the displacement for the obtained neural network control with $J_1 \to min$.

The solution of the second problem of transformation the frequency of the displacement on the back surface of the plate for cost functional J_2 is presented in Fig. 5. In this case for chosen class of neural network controls we have not achieved the high degree of the accuracy in transformation the frequency to the given value.

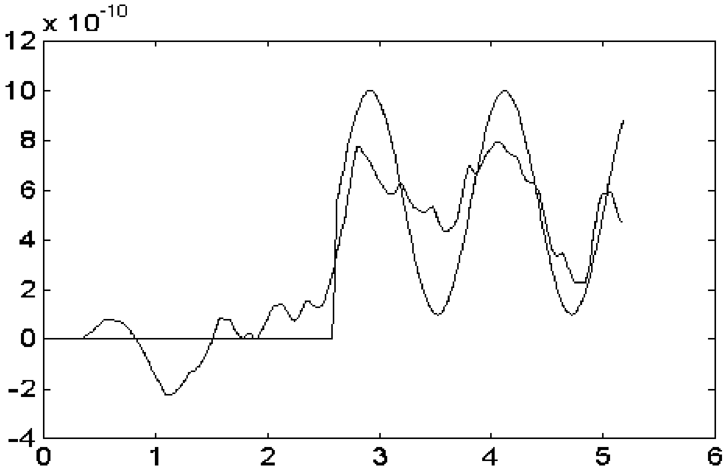

Fig. 5: The graphics $u_s^{opt}=f(t,\omega^{opt})$ - the defined optimal displacement ($\omega^{opt} = \omega/3$) and $u_s^{**}(t)$ - the displacement for the obtained neural network control with $J_2 \rightarrow min$, horizontal axis is time t (μs).

Conclusion

The problem of neural network control of elastic waves transformation during it propagation along thickness of laminated metal-ceramic plate when on the face surface of a plate is applied the oscillating pressure has been studied. The minimisation of quadratic cost functional depending on the velocity of vibration of the back surface of the plate and functional depending on the displacement of the back surface are performed as the adjustment weight parameters of synapse map of the three-layered artificial neural network. The input signals for neural network are the voltages of sensors piezoelectric layers and the output signals are the voltages applied to the actuators ceramic layers. The numerical results has been shown an ability of such mechanic-electronic system to suppress on the order the amplitudes of oscillations at the back surface of the plate and to transform (approximately) to a given value the frequency of oscillation.

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