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CONTROL OF COMPOSITE STRUCTURE DYNAMIC STATE ON BASIS OF NEURAL NETWORK APPROACH

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Abstract

The adaptive system of vibration damping for finite-element model of helicopter composite main rotor blade was designed. This control system include a neural network controller based on reference model, a bunch of distributed sensors measuring the local deformations in vibrating structure and piezoelectric power actuators acting on structure by local bending and twisting torques. The mentioned controller adjust a behavior of finite element model close to behavior of reference beam model that have a best parameters of structural damping, vibration stability and weight balancing. The control system model implemented in MATLAB Simulink© have shown an essential decrease of vibration level and suppression of rotor blade finite element model dangerous auto oscillations.

Key words: *smart structure, composite structure, active vibration damping, helicopter rotor blade, sensor, actuator, neural network*

1. INTRODUCTION

The most principal feature of the V/STOL (vertical or short takeoff and landing) flying vehicles future genetion is the refusal of a rigid passive carrying surface for the benefit of “active”, “adaptive”, “morphing”, or “intelligent” structures (Sater et al., 1993). Last years this problem is a subject of intensive researches of the leading air corporations and scientific schools. The properties of a wing activity are most evidently appear at flying insects having an exclusive maneuverability, which is achieved because of ability to adaptive change of geometry and distributed mechanical properties of the morphing wings. It is expected that the ability of the helicopter main rotor blade to controlled change of twist and local stiffness during a part of a rotor cycle revolution, will allow to improve the flight performance, controllability in critical situations, to lower of the noise and vibrations level, the load of all rotor design, to improve a survivability at local damages of blade's hollow sections (Rodgers et al., 1998: Hodges et al., 2003). The design concept and technical realization of a control system for active composite carrying structure is considered in the present article.

It is known that the forward flight almost always produce the vibrations of the completely balanced helicopter rotor. It is known also (Johnson, 1994), that on the hub of the main rotor with k - blades there are forces acting in a plane of rotation and in a plane of thrust with frequencies $kn\omega,(n=1,2,...)$, where n - number of a harmonic, ω - frequency of the rotor rotation. Besides, the flap movements of the blade create the Coriolis forces with harmonics of the following order, creating a complex interference picture of acting forces. In practice a movement of the blade relative to the horizontal hinge and its rotation in the axial hinge cause also the periodic forces, which amplitudes are appreciable up to tenth harmonics anyway. In flight the distribution of loading forces along the blade periodically varies, and these variable loadings can cause a resonance on one of eigenfrequencies of the blade.

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Traditionally for damping of resonant vibrations amplitude use constructive measures, for example, selection of the certain relations between own first flexural and torsional vibrations frequencies. However, at occurrence of such resonances the exciting forces are counterbalanced only by aerodynamic and structural damping of the blade material.

For reduction of a vibrations level aspire to increase of the blades material structural damping, to increase of number of blades, their trailer speed (Leishman, 1990).

The vibro-isolation of the rotor from airframe theoretically also it is possible to supply at small blades weight relative to a fuselage weight by way of the hub manufacturing as a dynamic damper adjusted on required frequency. Such means is not applied in practice because of the large overall dimensions and weight of similar dampers. Besides they are completely inefficient for suppression noise created by blades.

The rotor blade of the modern helicopter is made of composite materials, has essentially major structural damping versus metallic blade, and because of the greater flexibility can undergo a major strain. The blade of the middle-sized helicopter has close to a rectangular plane form, span length 7…8,5 m, chord 0,5 … 0,65 m, and twist ranging from +4 6 up to -1,5.. 2,5 degrees. The basic load-bearing element of the blade - spar, is made or level-by-level packing of reinforcing fiber glass fabric, or spiral winding by unidirectional fiber glass tape, stacked on epoxy resin symmetrical to an axis of the spar. Root parts of the spar usually strengthen by packets of a titanium foil and fiber glass fabric. The maximum centrifugal forces and tensile stresses have the order consequently of 20 … 25 ton and 80 … 100 MPa.

The known experimental architectures of the geometry and vibrations intelligent control (Jin et al., 2005; Gardonio et al., 2005; Seong et al., 2005) include a group of a strain gages and power piezoelectric actuators bonded on a surface of controlled structure, or embedded between layers of composite material. The intelligent control system treats the information from sensors and hand out signals in a real-time. These signals drive the actuators which change the dynamic stress-strain state and damp the load-carrying structure vibrations (Figure 1). Because of it a rotor disbalance, noise and total vibrations level decreases, and prevent occurrence of critical modes. Successes in development of similar systems (Li et al., 2006; Salman, 2005; Rajasekaran, 2002; Valoor et al., 2001) are achieved, basically, on the neural network-based approach.

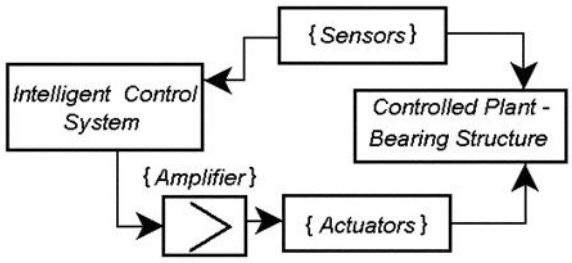


Figure 1. Concept of intelligent control of bearing structure's dynamics

Unfortunately, the lack of suitable mathematical foundations does not allow to a priori selecting the most effective architecture of neural network. Its design is yielded on the basis of the exhausting information on dynamic of a controllable mechanical system and, mostly, error method.

2. THE NEURAL NETWORK – BASED ARCHITECTURE OF STRUCTURE'S VIBRATION DAMPING

The architecture of a control system closest to the purposes of the present work contains two neural networks: networks - identifier and networks – controller (Valoor et al., 2001) (see figure 2). It is

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evident (in any case, while we do not have the sufficient information to consider differently) each network should have a number of hidden layers depending on complexity of a structure dynamic state. In dynamics operation of network quantized, i.e. the acting signals are treated not continuously, and in discrete instants. Thus the continuous time t is substituted by discrete time t_k:

$$t \to t_k = k \times \Delta t \to k\,.$$

The input signal of network – identifier is the signals from all sensors $\{V_s(t-\Delta t)\}$ and voltages from the controller to actuators $\{V_{ac}(t)\}$. An output of the identifier - new predicted signals from sensors $\{\overline{V}_s(t)\}$. The input signal of network – controller can be signals from sensors $\{V_s(t-\Delta t)\}$ and actuators $\{V_s(t-\Delta t)\}$ at preceding sample time. From an output the new signals $\{V_{ac}(t)\}$ operate on actuators.

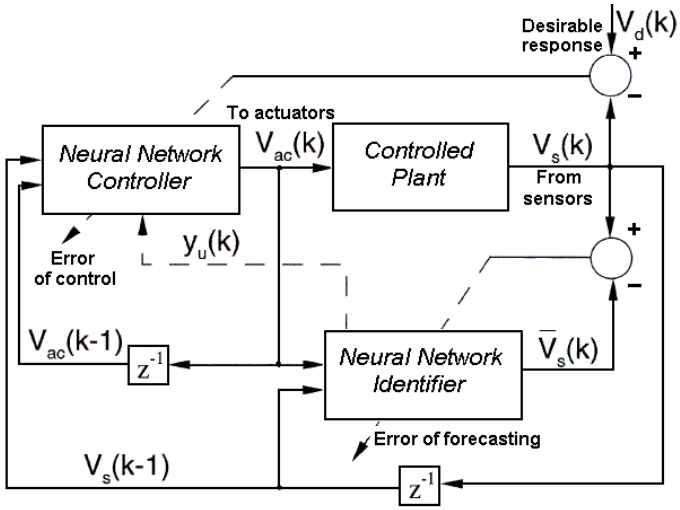


Figure 2. Neural network architecture of system for structure's vibration adaptive control (after Valoor et al., 2001)

The devices indicated in a Figure 2 by blocks z^{-1}, memorize of signal at preceding sample time. Selected signals of errors of a system's dynamic state forecasting are

$$E = 0.5\sum_{k=1}^{N_s}\left(\overline{V}_{sk} - V_{sk}\right)^2 = 0.5\sum_{k=1}^{N_s}{\delta_{sk}}^2$$

and control signal

$$E_c = 0.5\sum_{k=1}^{N_s}\left(V_{dk} - V_{sk}\right)^2 = 0.5\sum_{k=1}^{N_s}{\delta_{ck}}^2\,,$$

where V_{dk} – desirable response and V_{sk} – registered response of systems by k-th sensor in each sample time are produced at network learning.

Feature of the given approach is that the investigated dynamic system should be completely defined; thus the selftuning control system will provide optimum control, if the exterior perturbations do not overstep the bounds of given amplitude and frequency ranges. However the contingencies are possible when the control is not defined. Just such situations introduce the greatest hazard, and for their

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elimination the systems of intelligent control are intended. This circumstance essentially restricts applying such approach for build-up of rotor blade dynamics intelligent control. On the other hand, at presence of a broad frequency spectrum of vibrations the scheme represented in Figure 2, apparently, can not provide satisfactory reaction rate, since it will utillize of registered parameters values only on two temporal layers - actual and preceding. Adequate restoring of the mechanical system dynamic state evolution needs increase of neural network inputs number, information contents about system in preceding instants and, naturally, number of temporal layers.

Our numerical simulations carried out with a neural network such type as depicted on a Figure 2 and controlling finite-element model of a beam have confirmed the basic result obtained in (Valoor et al., 2001) about efficiency of similar system for damping vibrations on two first eigenfrequencies. However, two and the triple increase of hidden layers, volume of learning sequenses did not result into an effective vibration damping of beam model at impulsive loadings.

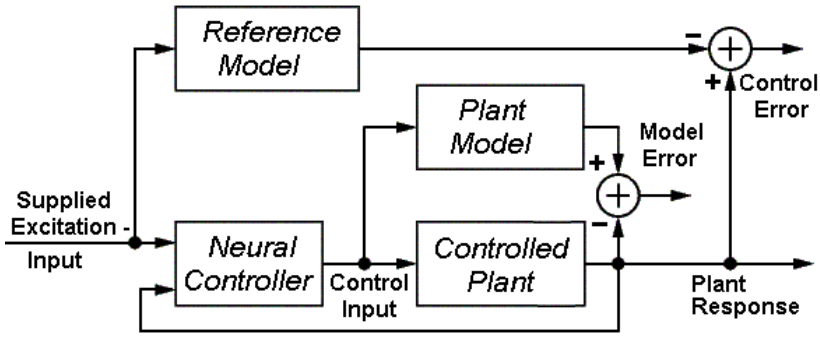


Figure 3. Architecture of control system based on reference model

For elimination of the marked limitation the control system architecture with use of master model (Model Reference Control) was designed (see Figure 3). According to (Hagan et al., 2002) in the beginning a model identification of a controllable mechanical system is yielded, then training of the neural network controller so that the output of controllable plant has match follows to an output of reference model. The structure of both neural networks contains a number of hidden layers, dependent by complication of controllable system - plant. The set of the controller input signals include: a delayed input of reference model; a delayed output of controller; a delayed output of a controllable system. The magnitude of delays can vary being increase with plant complication. The networks for mechanical systems simulation include two set of inputs: a delayed output of the controller; and delayed output of plant. The values of delays also are regulated in accordance with complication of controllable system behavior.

As reference model can be utilized an extreme simplified analytical or finite element model, maximum closest on dynamic responses to an actual controllable structure. An indispensable requirement superimposed on reference model, is it much improved behavior in critical situations (flutter, local damage etc.) at the expense of a heightened stiffness and structural (often nonlinear) damping.

Because of plant is a distributed mechanical system working in a frequency range cover to several first vibration modes, the considered architecture requires major volume of computations at stage of controller's learning and well balanced reference model. Furthermore that training teamwise with substantial mechanical system is represented difficultly implemented, adequate model of the plant – helicopter rotor blade required. The most perspective way is the making of blade finite element model and performing on it massive numerical simulations with the purpose of development of learning sequences.

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3. FINITE-ELEMENT (FE) MODEL OF PLANT – HELICOPTER MAIN ROTOR BLADE

3D models built by Catia v.5 on the basis of a full-scale blade design. For a guaranteed reliability of results the finite element analysis executed independently in ANSYS-10, Comsol Multiphysics 3.2, and ACELAN; all mathematical calculations - in MathCAD 11, MATLAB 7.3. That the properties of created 3D models were maximum close to dynamic responses of a full-scale blade the imported points of a blade spar cross-section optimally transformed to the spline representation specific to the used finite element program. The coordinates of spar sections were read as the text file by the program - converter translated points of sections to spline representation (rational curves Bezier and NURBS), ensuring thus minimization of splines coordinates deviation from a theoretical profile. The sketch of blade design and it finite-element model are demonstrated on Figures 4 and 5.

Along blade spar the cross-sections considering the hollow trailing sections the accurate (in geometrical sense) finite-element models were designed. On this basis the static characteristics and natural vibration modes were tested. However for major computational complexity of such models in the helicopter rotor blade at finite-element analysis some distinctive parts selected, which one modeled by relative simple geometry and homogeneous properties (Figure 5, a).

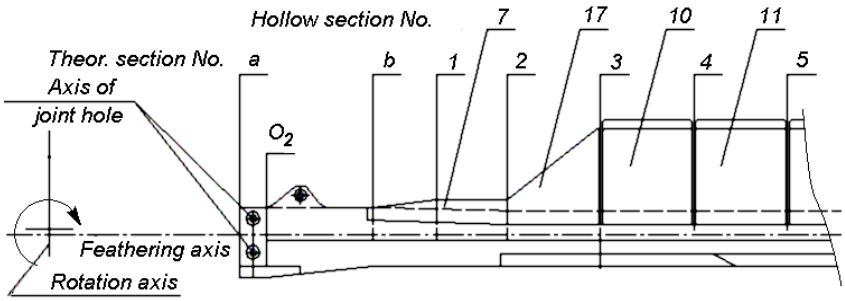


Figure 4. Piece of the modeled blade sketch

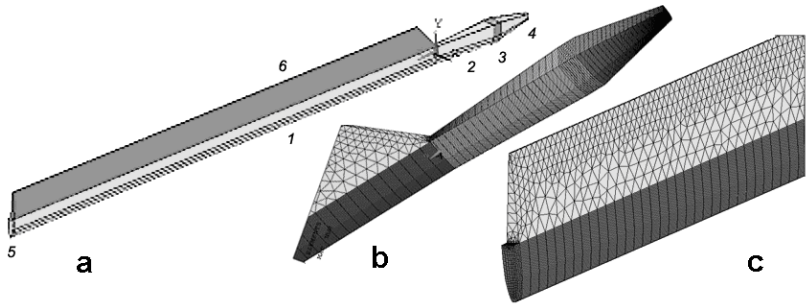


Figure 5. The simplified rotor blade finite-element model
a – full view; b – near root; c – near tip

In subdomains V_q, $q = 1,2,...6$ we have the equations of elastic body

$$\sigma_{ij,j} = \rho \ddot{u}_i \ (-\rho\omega^2 u_i), \quad \sigma_{ij} = c_{ijkl} u_{k,l} \quad i = 1,2,3$$

and boundary conditions on exterior boundaries $S = S_u \bigcup S_t$:

$$u_i|_{S_u} = u_i^0, \quad t_i = \sigma_{ij} n_j|_{S_t} = p_i,$$

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where u_i, n_i - components of displacement and normal vector respectively, σ_{ij}, c_{ijkl} - components of a stress tensor and elastic constants, ρ - density, ω - angular frequency.

The problem was raised in weak formulation, and its solution was searched in finite-element representation

$$\mathbf{u}(\mathbf{x},t)=\mathbf{N}_u^T(\mathbf{x})\cdot\mathbf{U}(t)\ ,$$

leaving to the differential equations for vector of nodal variables $\mathbf{a}=[\mathbf{U}]^T$

$$\mathbf{M}\cdot\ddot{\mathbf{a}}+\mathbf{C}\cdot\dot{\mathbf{a}}+\mathbf{K}\cdot\mathbf{a}=\mathbf{F}$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$, $\mathbf{F}$ - matrices of masses, damping, stiffness and vector of nodal loadings respectively. At modal analysis achievement the generalized eigenvalues problem was considered

$$\mathbf{K}\cdot\mathbf{a}=\omega^2\mathbf{M}\cdot\mathbf{a}$$

The comparative calculations of eigenfrequencies and natural vibration modes were performed in finite-element packages ACELAN, ANSYS and Comsol Multiphysics. With respect to character of blade bracing in the elastomeric bearing box of rotor hub modal analysis is carried out and the first 7 eigenfrequencies and vibration modes (see Figure 6) are determined. On a presented investigation phase the influence of centrifugal forces was leave out of this study framework.

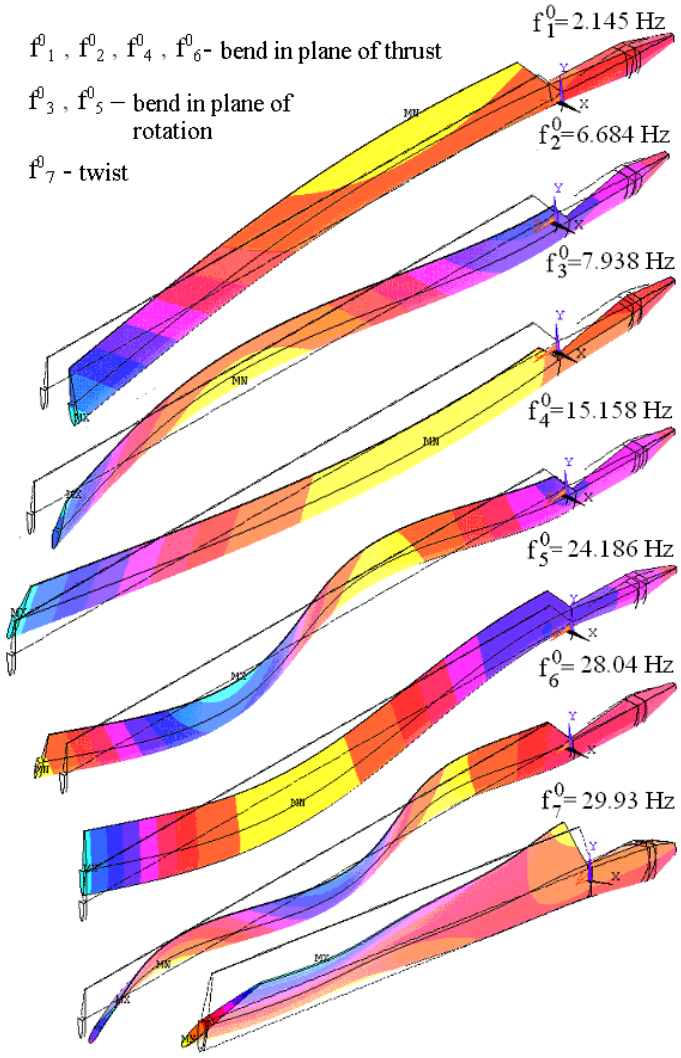


Figure 6. First vibration modes of model blade

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Obtained finite-element and beam models were utilized for modal and non-stationary analysis, showing the good agreement. The modal analysis (Figure 6) has revealed the allocation of eigenfrequencies and amplitudes distributions, thus, allowing a rational placement of actuators for extinguishing undesirable vibration modes, and also eliminate dangerous proximity of eigenfrequencies for flexural and torsional modes. For use as reference model obtained beam model was modified by increase of stiffness, viscous damping and translation of an axis of centers mass in flight direction.

4. CONTROL SYSTEM MODELING

The convenient tools for design and simulation of neural network-based dynamic systems in MATLAB and Comsol Multyphysics capabilities for export finite-element models in Simulink have predetermined a choice of these programs for making model of rotor blade dynamics control system. In numerical experiments have utilized from 2 up to 8 sensors and separately controllable actuators, placed on top and bottom surfaces along a reference beam and controllable plant. The neural network controller (No 3 on Figure 7) contained from 2 up to 5 hidden layers and up to 7 delays; the value of sample time 5 ms. An amount of nodes in finite-element models varied: for reference beam - 120…400, for plant - 14000…80000. All simulations were performed in 64-bit versions of the programs under Windows XP-64. Behavior of system inspected on time charts of flapping movement and angular displacements (angle of attack) of separate blade section. The case history of control system with neural network controller having 5 hidden layers and 5 delays is shown in a Figure 8.

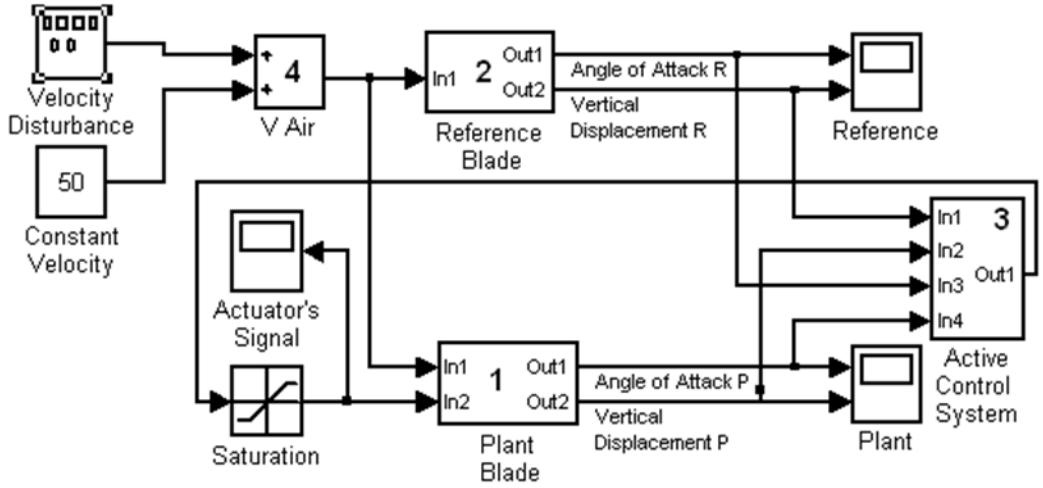


Figure 7. Simulink - model of neural network system for vibration damping of rotor blade finite element model

In lack of control signals at critical airflow velocity 60 m/s the vibratory instability - flutter of blade model arise. The frequency of elastic vibrations decrease, and the amplitude accrues sharply (see Fig.8, b, d) meanwhile the oscillations of reference beam is stable (see Fig. 8, a, c).
After run-up of the controller (Fig. 8, e, f) because of the expense of stiffness and structural damping the vibration amplitudes of a transverse displacement and angle of attack after short transient (3-4 periods) are drop down and stabilized - the flutter not arise. The duration of this transient is determined by an amount and power of used actuators. On the Simulink-model the ultimate actuators output was limited by saturation blocks.

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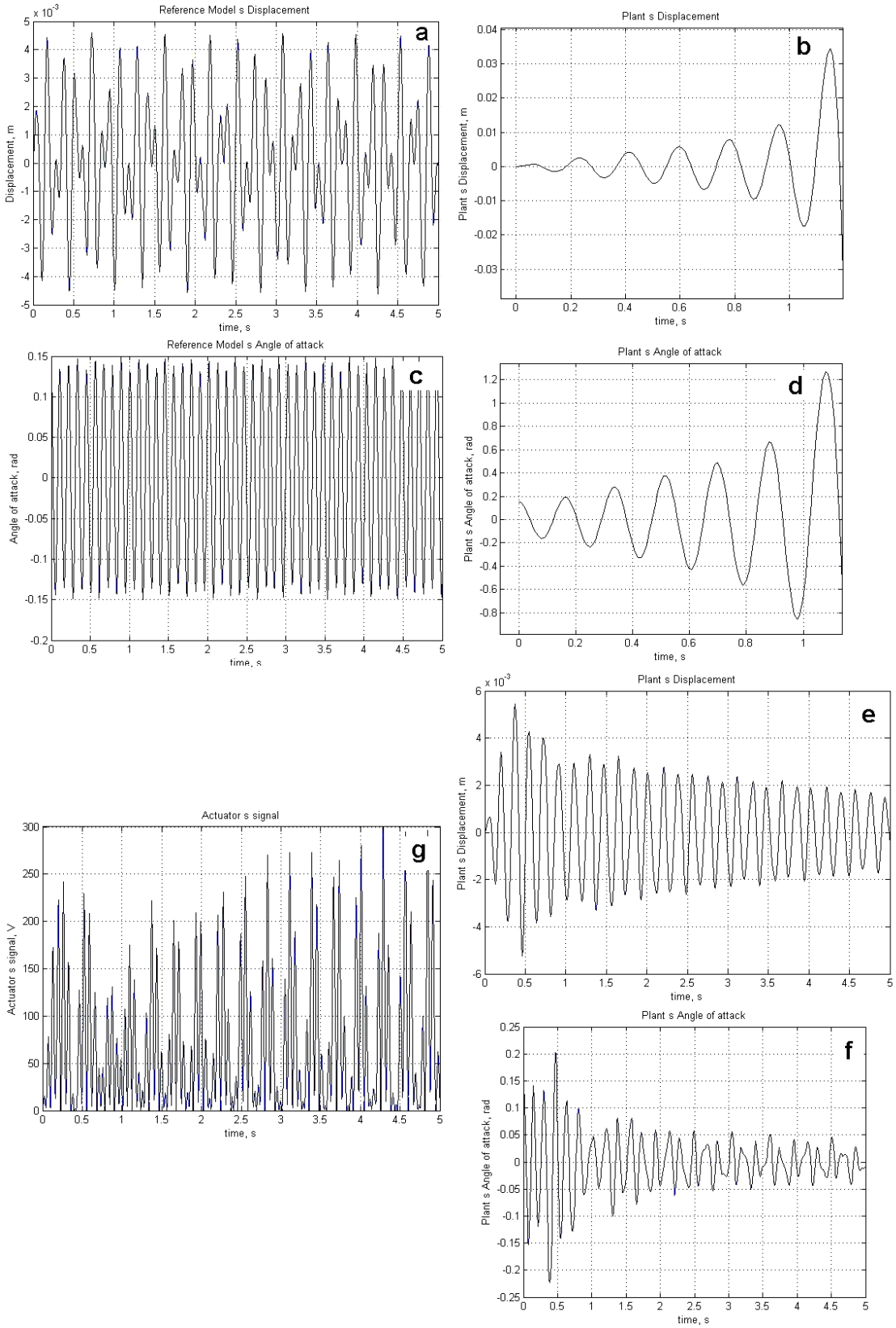


Figure 8. The time charts of displacement and angle of attack at airflow speed 60 m/sec:

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a, c - near reference plate tip;
b, d – near tip of the rotor blade unruled finite element model (shown on figure 5);
e, f - near tip of the rotor blade finite element model with active neural network controller;
g – electric potential on a piezoelectric actuator

5. CONCLUSIONS

The realization of proposed system has required considerable volume of computational operations at stage of the neural controller training for development about 10 thousand learning vectors. However experience of operation with created model and the first experimental results obtained on apparatus for study of composite plate auto-oscillations, have shown, that due to flexibility and speed of implementation in real time the architecture of control with reference model is represented as most perspective.

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