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INSTRUMENT-MAKING AND INFORMATION-MEASURING SYSTEMS

ПРИЛАДОБУДУВАННЯ ТА ІНФОРМАЦІЙНО-ВИМІРЮВАЛЬНІ СИСТЕМИ

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PROBLEMS OF INTELLECTUALIZING IN THE SHM SYSTEMS: ESTIMATION, PREDICTION, MULTI-CLASS RECOGNITION

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Summary*. The paper is devoted to the research of the efficiency of solving the intellectualization problems of multi-channel systems for the structural health monitoring of complex spatial objects with welded joints - tanks with ecologically hazardous substances. Based on the monitoring models of the object a visualization subsystem is developed for the reflection and prediction of the stress-strain state characteristics, spatial position and vibration state. The use of a classifier based on a probabilistic neural network has been developed for the multi-class recognition of structural health of the tank with the multi-site damage. Learning and test sets of the incoming multidimensional vectors of diagnostic features have been formed, classifier training and multi-class recognition in the case of structural degradation have been performed. The dependencies of the efficiency of the classifier on the parameter of the network influence for different values orders of diagnostic features have been found.*

Key words*: structural health monitoring, visualization, prediction, multi-class recognition, neural network classifier, efficiency of recognition.*

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Statement of the problem. Providing reliable and effective operation of the complex spatial objects with welded or riveted joints of the structural elements is the pressing problem for the aircraft engineering, oil and gas industries and special-purpose engineering facilities. To solve this problem it is required to provide the multi-class diagnosis to recognize the micro-defects in time, to estimate their sizes monitoring their development and interaction on the great sizes surfaces of the complex special objects.

Analysis of the available results of investigations. To diagnose damages in order to determine the current structural health of objects the method of non-fracture control and structural diagnosis are used, which are the most available for the certain facilities type, conditions and regimes of their operation and provide the required data on their sensitivity, efficient operation and reliable control. But for many complex spatial objects being operated in the critical conditions and characterized by the strict requirements as to their running without break-down, the problem of prediction damages, which can result in the structural elements fracture, is of great importance. The complex monitoring systems basing on the concept Structural Health Monitoring (SHM) [1, 2] are becoming available now. One of the specific

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features of the SHM system is the introduction of the modern computer-integrated technologies and intellectualizing, in fact, of all monitoring stages. The organisation of the monitoring intellectual systems is supposed to divide the functions into some subsystems or separate systems, which are its certain stages in the general monitoring procedure, which have its class of problem solving, its algorithm and software [3 – 5].

The Objective of the paper. To investigate the efficiency of the problem solving for the intellectualizing of the monitoring systems of the construction health of the complex spatial objects with welded joints-tanks with ecologically hazardous substances.

Statement of the task. In the [5] the multi-channel monitoring system was proposed for the functional diagnosis and monitoring of the structural health of tanks with ecologically-hazardous substances being in operation in almost inaccessible regions under the complex loading effects, in which the following has been implemented:

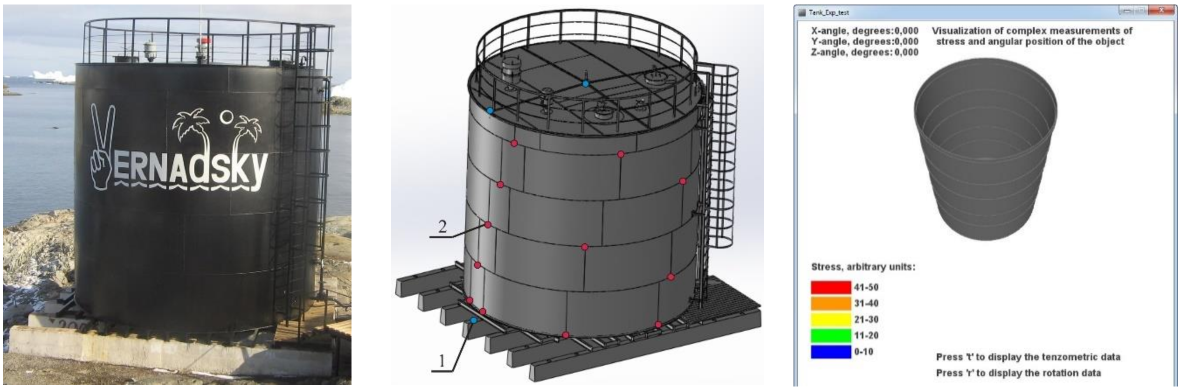
- the channels for the vibration measurement to control the modal characteristics of the tank, to control the vibration characteristics of the foundation, to determine the parameters and characteristics of the dynamic excitations;
- the channels of strain measurement to determine and control the stress-strain state characteristics of the tank external wall;
- the channel of inclinometry measurement to determine and control the spatial position of the tank under the dynamic excitations effect;
- the channel of the automatic measurement of the meteorological parameters being taken into account for finding the operation loadings on the tank.

Improvement of the system for the functional diagnosis and monitoring of the tanks structural health was proposed in the [6, 7] basing on the complex application of data on the vibration state, stress-strain state parameters and the spatial position of the facilities together with the application of the special diagnosis (monitoring) models. With this purpose, basing on the monitoring models of the objects, the visualization subsystem has been interpreted and developed to reflect and predict the stress-strain state, characteristics, spatial position and vibration state. For the multi-class recognition of the tank structural health, when multi-site damages are initiated and developed, the use of the classifier, based on the probabilistic neural network, was proposed and interpreted in the paper [8]. Thus, the improved system of the functional diagnosis and monitoring is the complex, multi-channel system, which includes the developed subsystem of the data visualization and the neutral network classifier, developed basing on the imitation modeling. The visualization subsystem and the state classifier are the examples of the monitoring systems intellectualizing, the implementation of which will provide the broadening of the functional possibilities of the monitoring systems, the possibility of localization and monitoring of the damage development on the sufficient surface of the spatial facilities, raising the reliability of recognition of the current structural health of the facilities predicting their changes.

Visualization of the measurement, estimation and prediction data. The subsystem of visualization was developed to reflect, estimate and predict the stress-strain state characteristics, spatial position and the vibration state of the tank in real loading conditions. The technologies of the motion grasp, as the basis for the reflection of the current structural health of the object as 3D-animation [9, 10], has been developed. The developed subsystem provides: implementation and control of the geometric model of the object; imitation of the object structural elements interaction; processing and transformation of data obtained from the sensors, their introduction into the object imitation model; imitation modeling and reflection of results on the object model.

In Fig. 1 the photo of the monitoring object is presented – fuel tank at the Ukrainian Arctic Station Academician Vernadsky, its developed three-dimensional model and the main window of the program for the visualization of the results for complex measurements of stresses and the spatial position of the object. To implement the visualization subsystem the algorithm and software were developed for the processing (transformation) of the input data in the file and their correct reflection on the imitation model of the tank, taking into account the perculiarities of the data reflection in the file, the analogue-digital transformer (rate, input range), the number of elements of the three-dimensional model for the data reflection.

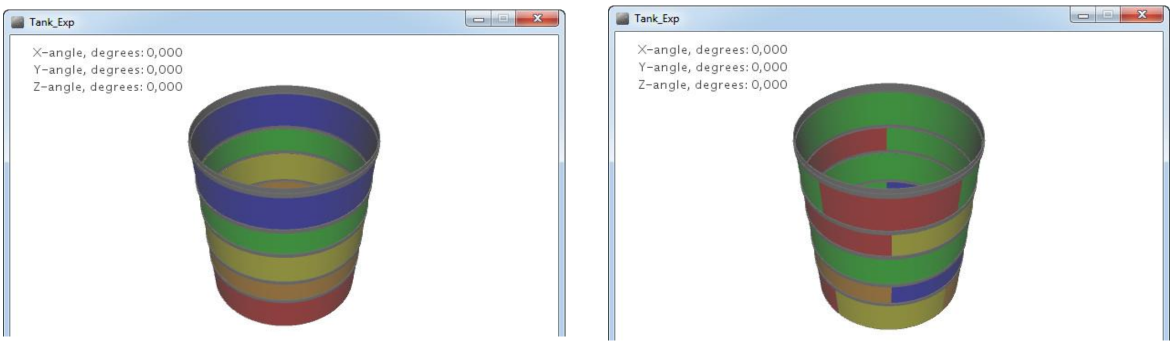
Basing on the programming language Processing, which makes possible to work with the three-dimension graphics, the reflection program of the strain measurements written in the file earlier was implemented on the geometric model of the object to reflect the current spatial position of the object by visualization of the measured inclination angles of the structure relatively the vertical axis.



a) b) c)

Figure 1. The photo of the tank (a), its three-dimensional model (b) with the scheme for the installation of sensors (1 – accelerometers and inclinometers, 2 – strain gauge indicators), the main window of the program of visualization of the current spatial position and strain gauge data (c)

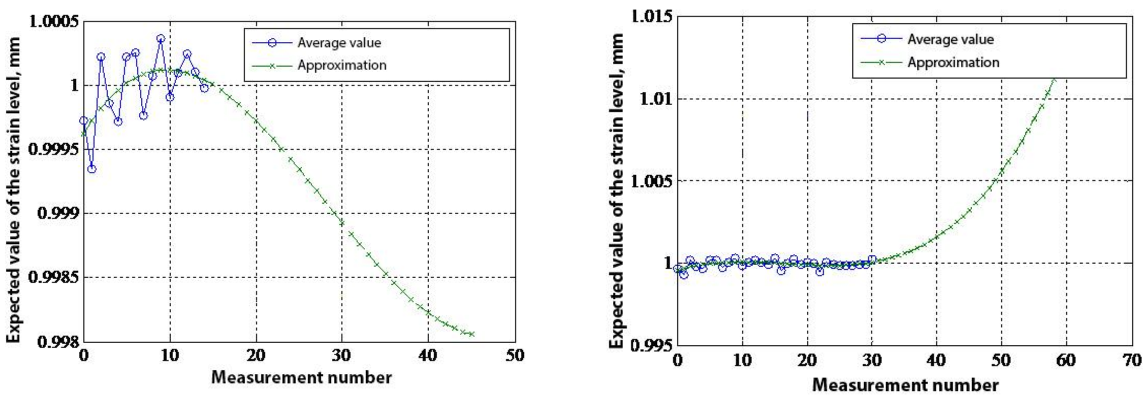
The software is implemented basing on the programming language Processing, which makes possible to work with the three-dimensional graphics. For the stresses five intervals of the data visualization were chosen, each of which being of its reflection data colour on the geometric model of the object. In Fig. 2 the results of the visualization system testing are presented on specially grouped data. The case, when every of the model zones is filled with the same type of data from the accepted five visualization zones, is presented in Fig. 5a, and the example of filling all model zones with the random data – in Fig. 2b. The program is versatile, depending on the real data the program code can be changed or increased for more precise correspondence to the tasks being solved.



a) b)

Figure 2. Examples of the results of visualization of strain gauge data a) filling of the model zones with the same type of data; b) filling of the model zones with random data

In the subsystem of visualization the program of the strain growth prediction and the graphs reflection as the trend extrapolation lines was implemented. In general, the trend model can be expressed due to many functions, basing on which the prediction model is formed and estimated. In fact, the most often linear, parabolic, exponential, step and logarithm functions are used. Extrapolation of the discrete function (model), by which the trend is described, makes possible to obtain the point value of the strain degree change prediction for the certain period of time. In this case the parabolic models, including the third level, have been used, the trend being found according to the average value of the strain signals model taking advantage of the smallest squares. The prediction of the strain degree change was carried out for the further 31 values. The models of the measurement signals were chosen in such a way, that the first 40 measurements specify the defect-free state of the structure, all the next possessing plastic deformation, which increases due to the linear law. The results of the strain growth prediction are presented in Fig. 3.



a) б)

Figure 3. An example of trend extrapolation for: a) 15 measurements; b) 31 measurements

The carried out investigations testified the possibility to raise the prediction precision, when the number of the input data increases, and the available regularity in the measurements will contribute to the increase of the approximation reliability. It was determined, that for the model of signals in question the accepted approximation reliability by the second and higher orders paraboloids is obtained only, when sufficient regularity in the measurement results is available.

Multi-class recognition. The complex spatial objects are usually characterised by great variety, non-stationary processes, parameters distribution, non-linearity, unsufficient control of the external effects, conditions and regimes of operation. In such conditions the probability of the multi-set damages initiation and development in the areas of welded joints (or riveted for the aircraft structures) occurs, which specifies the objects multi-class structural health in both spatial and time measurements. To recognize the state of the welded fuel tank the development of the neutral network classifier, included into the multi class system of monitoring, has been proposed and interpreted in the paper [8]. To recognise it the input multidimensional vectors of the diagnosis features, which are formed according to the results of the diagnosis information analysis, are used. The classifier sends the object to the determined classes of the functional state, which are specified due to the availability, dimension and damage localization depending on the recognition task.

To build the classifier the probability neural network (PNN) was used. It consists of two layers. The first layer neurons are of the radial-basis activation functions, and the second layer of neurons is the competition layer, which calculates the probability of the input vector being included into this or that class, and, finally, compares the vector with the class, the probability to be included to being higher. The classifier elements are: the training images set or diagnosis features (vector *P*); the aim classes set (vector *T*); the matrix of connectivity *Tc*, which determines the input vectors belonging to the certain classes; the neural network, which performs classification and recognition of the structural elements state, testing set (vector *Ptest*). The latter being changed into the real data set while functioning, which come from the sensitive elements set. Every input PNN vector has its corresponding input or aim value, and for the input and output values the vector of implementation input/aim is formed. The training set contains *Q* vector pairs input/aim. There are *K* classes, to which the input vector can belong. As a result the matrix of connectivity *Tc* can be formed of the *K* x *Q* size, which consists of 0 and 1. The lines of this matrix correspond to the class they belong to, and columns – to the input vectors. Thus, if the element *Tc(i, j)* of the matrix of connectivity equals 1, it means, that the j^{-th} input vector belongs to the *i* class.

The number of the first layer neurons is formed according to the vector pairs number input/aim of the training set. The output competition layer contains *K* neurons according to the *K* classes. In the paper [11] the task of the multi-class recognition is solved in the case of the structure degradation, when multi-set damages are initiated and developed. For the vector *A*, which possesses, for example, 5 features, the state of the controlling object is described by 6 classes: defect-free (S_0) and with different degree of the damages propagation ($S_1 - S_5$). General scheme of such classifier is presented in Fig. 4.

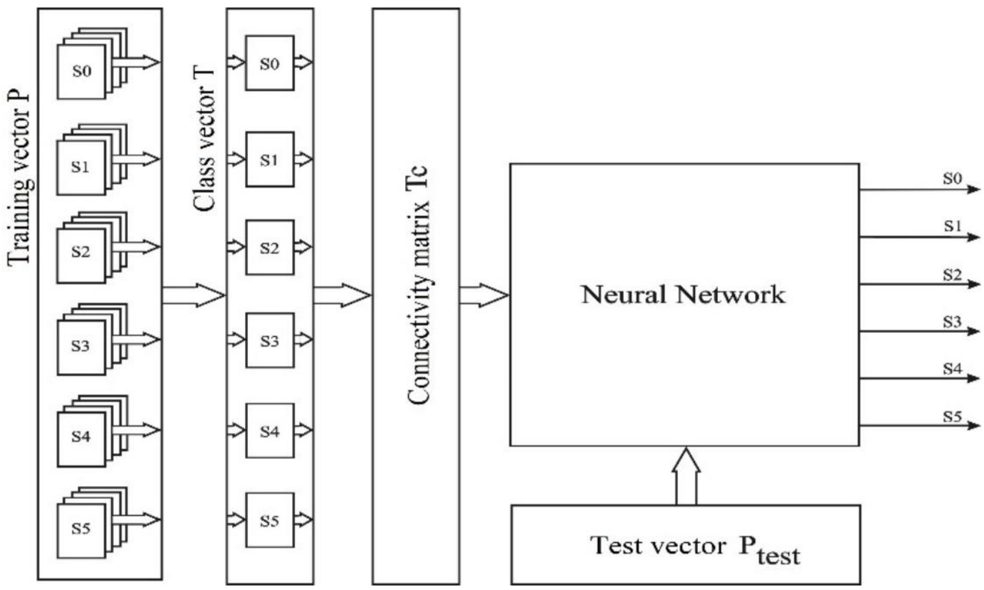


Figure 4. General scheme of neural network classifier

The principle of forming training and testing sets of the multidimensional vectors of the diagnosis features for different classes of the object structural health in the case of the structure degradation can be presented as the scheme in Fig. 5. The number of classes for recognition will depend on the dimension of the diagnosis vector *A*. For the class S_0 all the diagnosis features in the vector have the values with possible deviations, which do not exceed the permissible values Δ_0. Every class for the defect states will differ from the previous class by increasing the number of the diagnosis features in the vector, for which the deviation value Δ_i, Δ_j, Δ_n simultaneously exceeds the permissible value Δ_0.

For the classifier built on the PNN basis the choice of the network *spread* effect parameter is of importance. This parameter is connected with the average quadratic deviation of the Gaussian function, which provides the function spread of the first layer neurons activation and specifies their effect on the estimation of the total probability density [8]. That is why it affects the classification result and its maximum value is found experimentally while the network testing and the testing vectors classification, which provide the reliable recognition or that with the minimum possible errors.

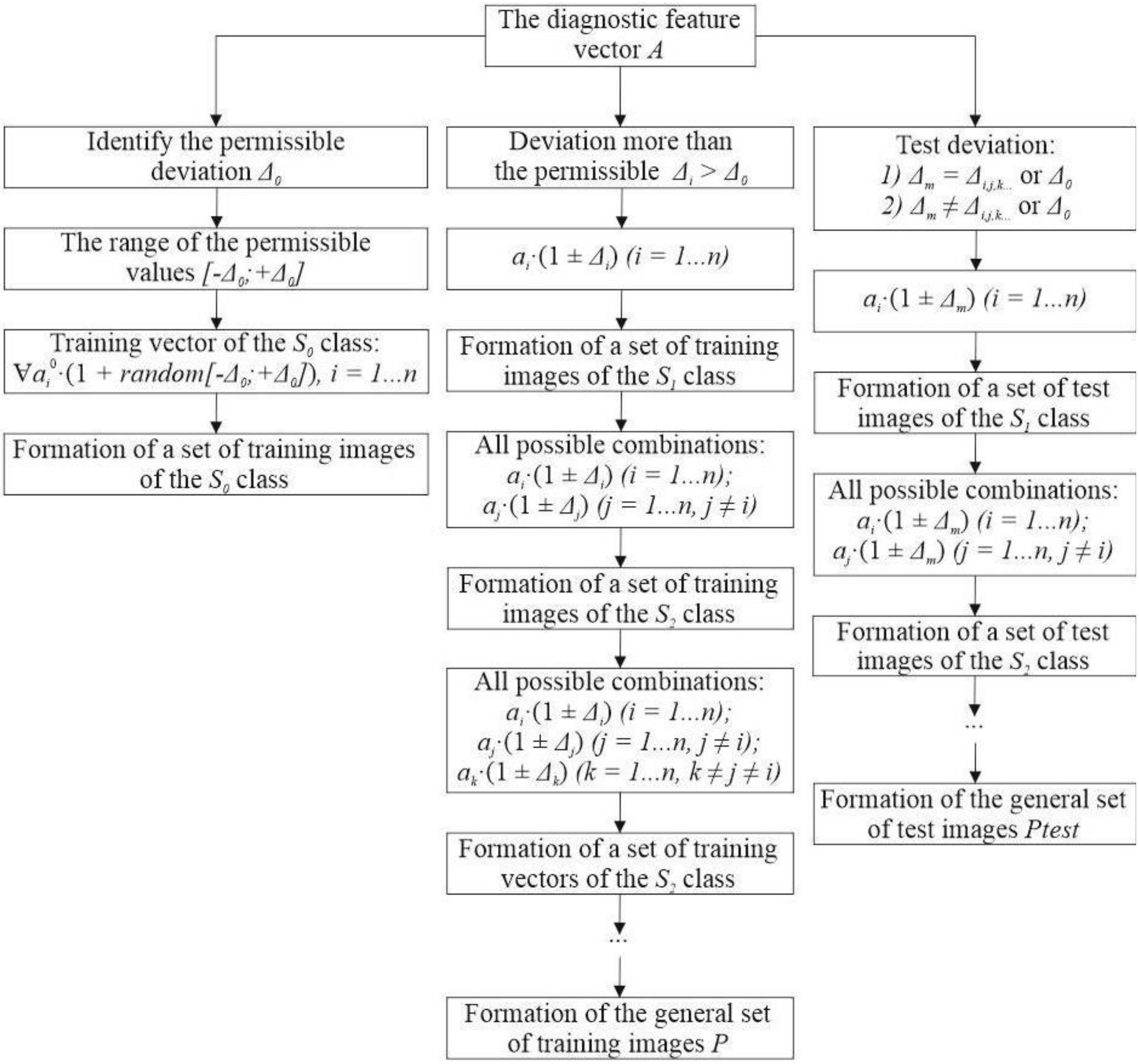


Figure 5. The principle of formation of training and test sets of multidimensional vectors of diagnostic features for different classes of structural health of an object in the case of structural degradation

Besides the PNN effect parameter the important factor of recognition are the numerical values of the diagnosis features themselves in the multidimensional vectors. It is caused by the fact, that the scattering of the feature values in the diagnosis vector for the defect-free and defect classes will differ greatly for the features of different order values.

Let us investigate the effect of the diagnosis features range, the values of the features deviation for the defect state classes and parameter of the network *spread* parameter on the classification efficiency. With this purpose due to the logarithm in Fig. 5 the formation of training and testing sets of the diagnosis vectors was performed, according to which multi-class recognition was carried out. The diagnosis vector *A* possessed 5features, the values of which were chosen from the intervals [0…1] and [0…10]. The value of the classification efficiency *K* was determined depending on the *spread* parameter as the per cent ratio of the properly classified testing vectors number to the general number of the testing vectors. The results of finding the *K* value for different deviation values of the diagnosis features for the defect classes Δ_m in the testing vectors are presented in Fig. 6 for the diagnosis feature values from the interval [0…1] and in Fig. 7 – for the diagnosis feature values from the interval [0…10].

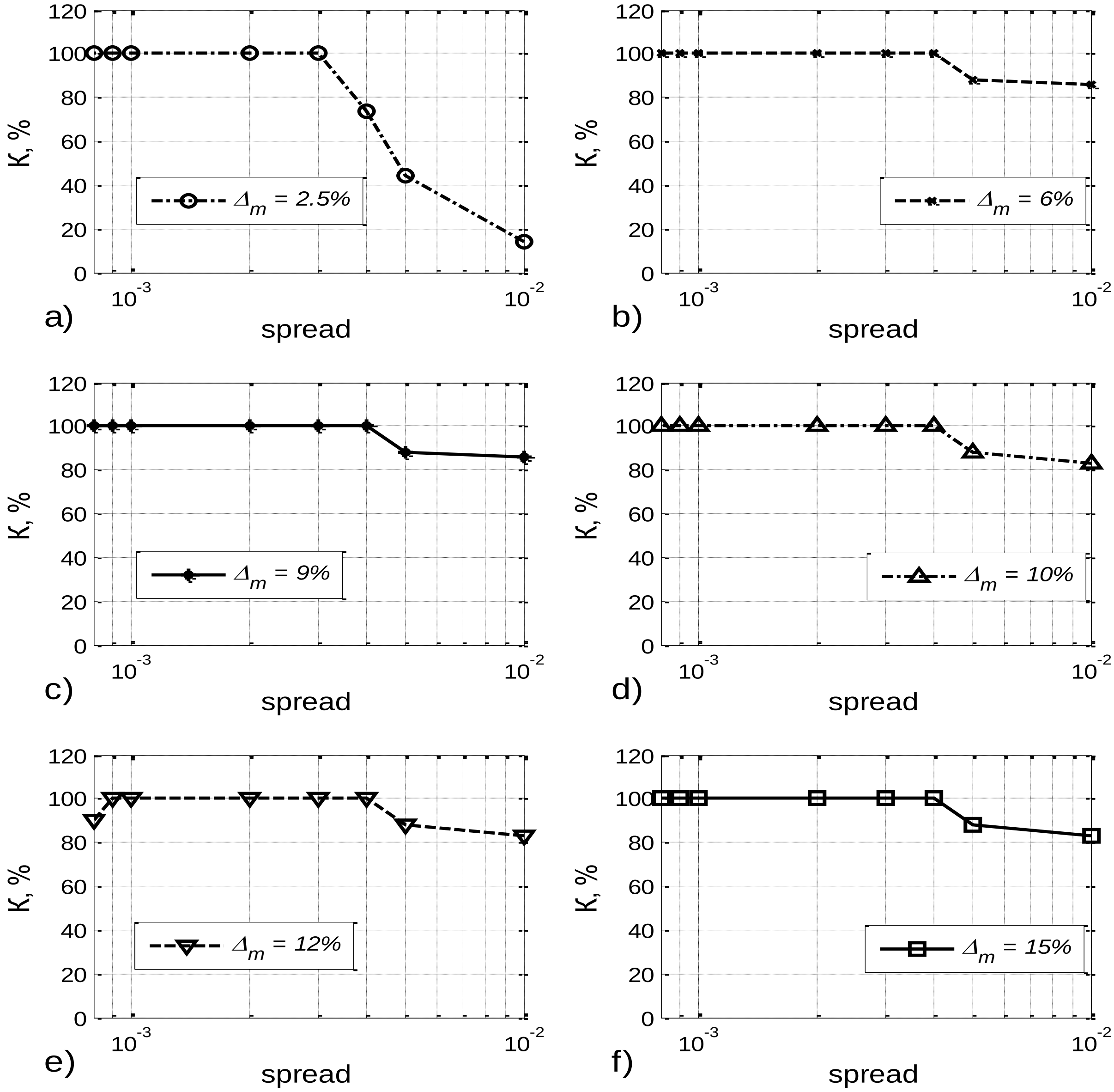


Figure 6. Graphs of the dependence of the indicator K efficiency on the parameter of the network spread effect at multi-class recognition for the diagnosis values from the interval [0 ... 1]

As it is seen from the graphs presented in Fig. 6 the developed classifier provides reliable multi-class recognition of the object structural health in the case of the structure degradation for all mentioned deviations Δ_m, if the values of the diagnosis features in the input vectors are within the interval [0…1]. The value of the network *spread* effect parameter, which provides the reliable recognition, is within the range [0,0009; 0,004].

When the feature values interval [0…10] increases, and the other parameters of the training and testing sets of diagnosis vectors are constant, the recognition efficiency becomes worse. As it is seen from the graphs presented in Fig. 7, there is no single range of the feature values effect of the network *spread* for all analysed deviation features Δ_m for the diagnosis features of different orders, in which the reliable multi-class recognition of the object state would be provided. The availability of such values interval for the deviations Δ_m=10% (Fig. 7,d) and Δ_m=15% (Fig. 7,f) is caused by the fact, that these deviations were used for the training and testing of the classifier. That is why in the general case the obtained result confirms the need to use the feature values of one order or their rating in the diagnosis vector.

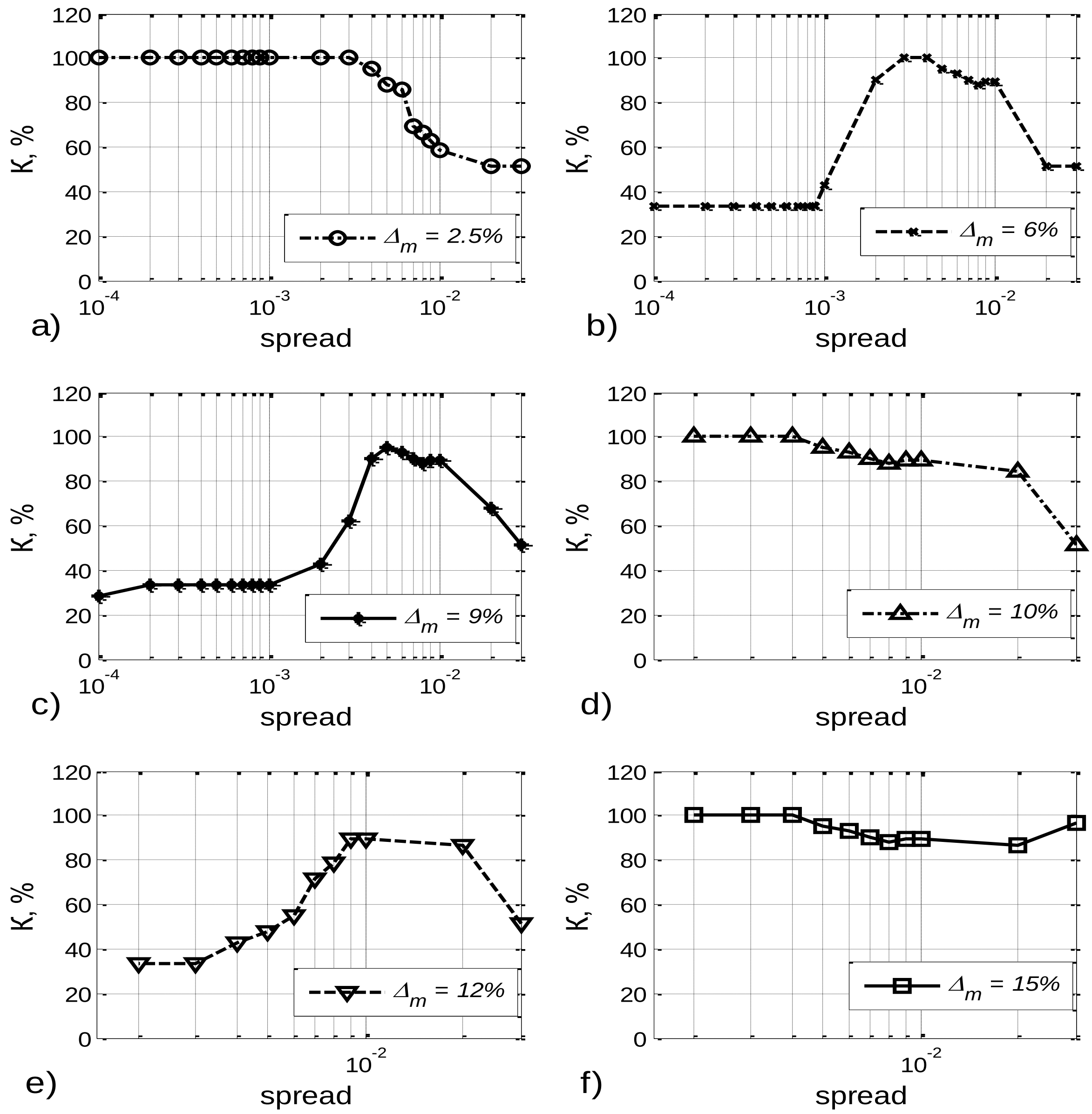


Figure 7. Graphs of the dependence of the indicator K efficiency on the parameter of the network spread effect at multi-class recognition for the diagnosis values from the interval [0 ... 10]

Conclusions. Basing on the imitation modeling the subsystem of the measured data and the result of their analysis visualization has been developed, in which the source of information can be the data obtained from the sensors of initial information mounted on the object, mathematic models of the measuring channels, compiled files containing the measurement data or the results of modeling. In the visualization subsystem the programs for the prediction of the strain growth in the conditions of the operation loadings were implemented and graphs as the extrapolated lines of the trend were plotted. It was determined, that the prediction reliability increases, when the number of the input data is greater, and the revealed regularity in the measurements will contribute to the increase of the approximation reliability. The classifier based on the probability neural network for the multi-class recognition of the tank state in the most hazardous case of damages propagation and development has been developed and implemented in the program. The principle of formation of training and testing sets of multidimensional vectors of the diagnosis features for different classes of the structural health of the facilities in the case of the structure degradation has been developed. The dependences of the classifier efficiency value on the parameter of the network effect at different values intervals of the diagnosis features and the values of their deviation have been obtained. The value range of the neural network parameter effect for providing the reliable classification of the determined states of the object for the recognition according to the diagnosis features, the values of which are in the interval [0…1], has been found. The recommendations as to the coordination of the diagnosis features values in the multidimensional vector for providing the recognition reliability, have been developed. The results of the carried out investigations have testified the efficiency of the developed means of intellectualization of the multi-channel systems of monitoring for the complex spatial facilities, for the solving of such tasks of the multi-class diagnosis as the measurement data visualization, prediction of the object state, multi-class recognition in particular.

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ПРОБЛЕМИ ІНТЕЛЕКТУАЛІЗАЦІЇ В СИСТЕМАХ SHM: ОЦІНЮВАННЯ, ПРОГНОЗУВАННЯ, БАГАТОКЛАСОВЕ РОЗПІЗНАВАННЯ

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Резюме. *Досліджено ефективність вирішення завдань інтелектуалізації багатоканальних систем моніторингу технічного стану складних просторових об'єктів зі зварними з'єднаннями – резервуарів з екологічнонебезпечними речовинами. На основі моніторингових моделей об'єкта обґрунтовано та розроблено підсистему візуалізації для відображення та прогнозування характеристик напружено-деформованого стану, просторового положення та вібраційного стану. Для багатокласового розпізнавання технічного стану резервуару при появі та розвитку багатоосередкових пошкоджень обґрунтовано використання класифікатора на основі ймовірнісної нейронної мережі. Сформовано навчальні й тестові множини вхідних багатовимірних векторів діагностичних ознак, виконано навчання класифікатора та багатокласове розпізнавання стану у випадку деградації конструкції. Встановлено залежності показника ефективності класифікатора від параметра впливу мережі для різних порядків значень діагностичних ознак.*

Ключові слова: *моніторинг технічного стану конструкцій в експлуатації, візуалізація, прогнозування, багатокласове розпізнавання, нейромережевий класифікатор, ефективність розпізнавання.*

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