SMART COMPOSITE STRUCTURE OF SELF-ADAPTIVE STRENGTH*

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Abstract: This paper introduces smart composite structure which consist of inorganic nonmetallic composites and in which sensor arrays(polarizing optical fibers and resistance strain wires) are embedded and shape memory alloy(SMA) foil is mounted on the surface. Self-adaptive and self-diagnostic functions are achieved by a micro-computer using high speed parallel processors and neural network software. The article discusses: (1) the experimental results of strain changes and the natural frequency vibration changes after the SMA foil is excited ,(2) the arrangement of the SMA foil by which the structural stress conditions can be improved, and (3) self-adaptive and self-diagnostic systems using neural networks.
Key Words: self-adaptive and self-diagnostic strength, inorganic nonmetallic materials, smart composite structures

Introduction

Composite materials are widely used because their greater comparative strength enables flight vehicles to shed weight. With the development of materials science, various new high-strength composites are continually being developed and substituted for metal materials in ever wider applications. However, composite materials possess more complex mechanical properties, damage behaviour and technologies than those of metal materials. For example, after suffering an inpact load, the appearance of a composite structure may appear normal but internal damage can be extensive, including composite delamination[1][2]. Moreover gas holes and other internal defects may be present in the composite as a result of the manufacturing process. If damage to a composite structure can be datected and the spread of damage can be prevented by applying real-time self-adaptive and self-diagnostic processes, then the range of applications of composite materials in flight vehicles will be greatly increased.

SMA foil and sensor arrays (optical fibres and resistance strain wires) are embedded in the composite, and the location and level of damage are detected by the sensor arrays and determined by a high speed parallel processor using a neural network system. The SMA foils in relevant areas are then excited by signals from the controlling system in order to improve the stress state of the composite structure and enable the structure to possess self-adaptive and self-diagnostic functions.

The following are discussed separately below: the distribution of the SMA foil, the polarizing optical fiber array, the resistance wire array, the neural network processor and the test results of the self-adaptive and self-diagnostic composite structure.

The Function and Distribution of SMA Foils

The SMA has the Shape Memory Effect(SME) If the SMA is deformed within plastical range at a ambient temperature, it will regain its original size after being heated over the actuating temperature[3]. We choose NiTi SMA whose diameter is 0.3mm~0.5mm or thickness is 0.3mm. The foils can be corroded into various configurations (the corrodent involves HF 2.4%, HNO_3 2.4% and distilled

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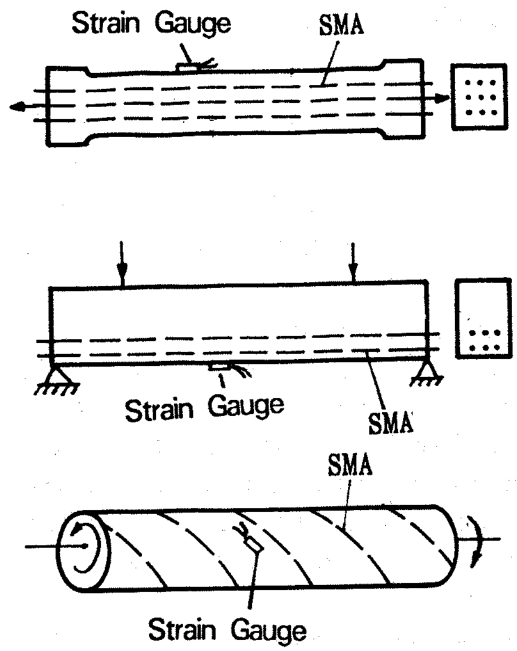
water 95.2%). The percentage elongation of them is about 15% and the actuating temperature is at 55℃. ~ 60℃. After special handling and the 6% deformation at a ambient temperature, the SMA will regain its original size in full by the electric current actuating. The SMA can be used repeatedly. During the regain, the SMA may exert a greater regain force.

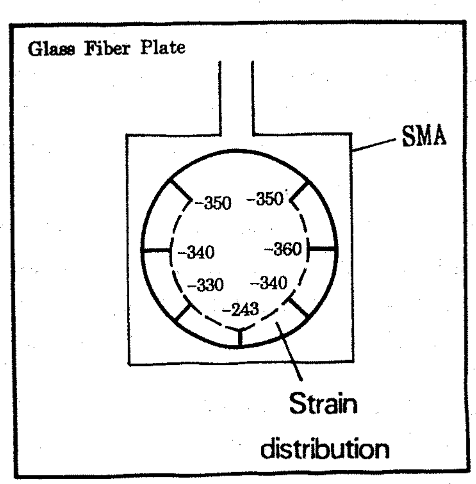
The SMA wires are embedded in a composite structure made of glass fiber and epoxy resin to improve the strain state.When the SMA wires are actuated,the strain change is shown in figure 1. and the strain values are respectively listed, which report the variation of the strains in tensile, pure bend and twist samples. The results measured using strain gauges show that the strain values are much lower than those before the SMA wires act, so SMA wires can be used for sharpenning the bearing capacity of a structure. In order to simulate the damage caused by a bird crash or bullet hit (see figure 2.), we use a composite material plate with a hole around which SMA wires are glued, The experiment results show that the damage can be prevented from extending by the compressive strain caused by the actuated SMA wires. In figure 3, SMA wires are embedded in a cantilever beam which is driven with a actuator. While the SMA wires act, the intrinsic frequency of the beam can be cut down about 17.4% and the amplitude is 62.5% less than original resonate amplitued.

The experiments above express that SMA wires embedded suitably in a composite structure can reduce the tensile stress, improve the bearing capacity, avoid the damage extending,increase the safety of the structure, change the intrinsic frequency and alter the viberation modes.Applying boundary element method to calculate the local stress caused by the SMA wires, we obtain the consequence that the SMA wires embedded can produce a large local stress, (shown in Fig.2) so the SMA can be made into foils and sticked on a structure. The foils



Before the SMA is actuated	After the SMA is actuated
Tensile strain (μ ε)	
1960	1130
Bend strain on lower surface (μ ε)	
2650	1580
Twist strain (45°) (μ ε)	
1580	1300

Figure 1.Tensile,pure bend and twist samples with SMA wires embedded, and the test results.



The Strain Measurement With a Optical Fiber Array

Three types of embedded optical fiber strain gauges (twisted joint and micro-bended optic fiber, Mich-Znhnder interference optical fiber and polarization phase optical fiber) are used in the experiment. The results are obtained as follows: the sensitivity of twisted joint optical fiber is too low to be satisfied for measurement, the sensitivity of Mich-Znhnder interference optical fiber is high enough to detect the strain but the sensor is expensive to operate,and the polarization phase optical fiber is suited for test and is inexpensive. The polarization phase optical fiber is selected to form a array and make the measurement easily. Figure 5 shows the principle of a polarization phase optical fiber strain gauge. The light source is a laser diode, and a focused beam passes through a collimator and a 1/4 wave slice and enters the optical fiber embedded in composite. The varied strain can cause the change of polarization state and the optical phase output of the mono-mode optical fiber. The photodiode can detect the different light strength through the lens and polarizators.

The optic phase through a mono-mode optical fiber of length L may be expressed below:

$$\Phi = \beta L = K_o n L$$

where

- β — the constant of light progratins in a mono-mode optical fiber
- K_σ — Borzmar constant
- n — index of refraction

With the mathematical mothed, $\varepsilon = \frac{\Delta L}{L}$, (the axial average strain of a fiber) and $\varepsilon' = \mu\ \varepsilon$ (the radial strain) if the trace is ignored, we can obtain the formula:

$$\Delta\Phi = \{\beta - \frac{1}{2}\beta n^2[P_{12} - \mu(P_{11} + P_{12})]\} L \varepsilon$$

Where

P_{11}、P_{12} — the optic elastic constant of a optic fiber corn

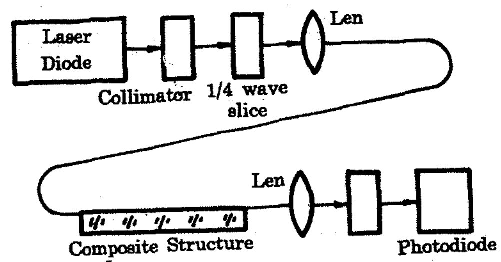


Figure 5. The principle of a polarizaion phase optical fiber strain gauge

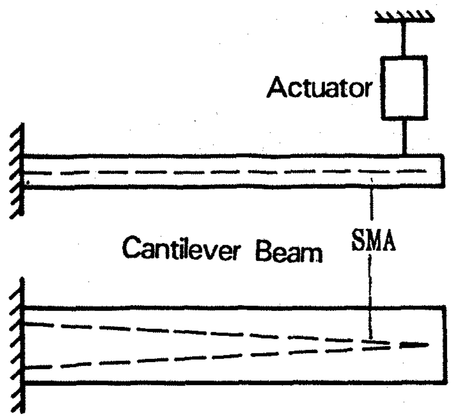
The Resistance Strain Wire Array

The performance of resistance strain gauge is steady and reliable.It is one of the sensing components most in use in strain measurement in a structure. In a composite structure, the distribuion of strain can be detected with it.By changing heat-treatment norm, we have got many kinds of self-conpensate resistance wire to adapt to various composite structures.The diameter of a wire is only 3～5 μm. When embedded,it causes less effect on the orginal strength of the structure and can be coupled well with materials.

As a sensing component,the strain wires are put voltage of 6～10v on. The pattern of temperature caused by the current in wires can be measured with a infrared image system Inrfametrsc600 and result shows that the temperature is only increased about 2～3 ℃ under normal operating condition. By special coating process, the connecting strength between a wire and composites will be improved and resistance wires can be used in the uninsulated composites (e.g. carbon fibre).

The arrangement of strain wires should be decided according to the shape of a structure and loading condition. For example, when a composite plate subjected to bending load,the synametric arrays can be respectively monnted on the two surfaces. The resistance wires correspondant positions can be used to form two arms of a bridge in order to increase the sensitivity,eliminate the influence of temperature and compensate each other. The test shows the

Figure 2.The strain distribution around a hole.(after the SMA actuated)



	Before SMA actuated	After SMA actuated
Amplitude(mm)	4.8	1.8
Intrinstic freqnency(Hz)	17.6	18.4

Figure 3.The cantilever beam with a SMA wire embedded and the test results

can also improve the bearing capacity and have a smaller influence on the original strength of the structure.

Figure 4 shows the arrangement of SMA wires in a composite structure.The SMA wires are sticked on the both surfaces of the plate. A basic unit on one surface shown in Fig. 4 consists of 4 sub-units, and each sub-unit consists of 4 elements and 11 lead wires. The sensor array and neural networks determine the position of a damage, the lead wires are connected to the power supply in reference to certain conditions and the SMA wires are actuated to cause the compressive stress around the damage region and improve the stress state.

For example,if there is a damage or hole in area [1], conncet the lead wires 2 and 3 to power supply,the SMA wires (1)-(2)-(10)-(9) are actuated, and the element [1] is in compressive stress state;If the SMA wire (9) is damaged,connect the lead wires 1 and 3 to power supply,the SMA wires (1)-(2)-

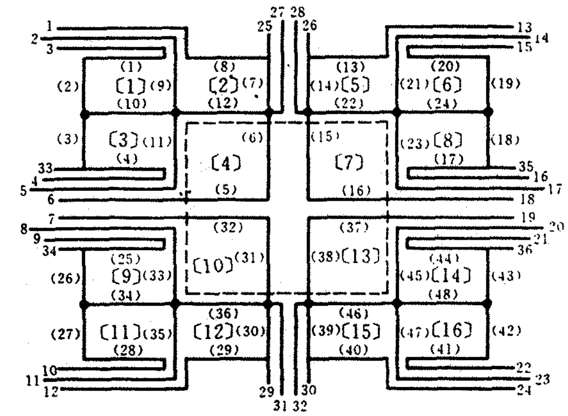


Figure 4.The arrangement of SMA wires to prevent a damage extending

(10)-(12)-(7)-(8) are actuated,and element [1] and [2] are in compressive stress state; If SMA unit (9)、(10)、(11)、(12) are been damaged, connect 4 and 6. at the same time connect 1、3 to power supply,the SMA wires (1)-(2)-(3)-(4)-(5)-(6)-(7)-(8) are actuated, and the basic unit [1]、[2]、[3]、[4] are in compressive stress state;If SMA wires (4) and (25) are damaged, short lead 33、34, connect lead 5 and 8 to power supply, the SMA wires (11)-(10)-(3)-(26)-(34)-(33) are actuated and the element [3]、[9] are in compressive stress state; If SMA (7)、(14)、(6)、(15)、(12)、(22) are damaged,short 25 to 26,27 to 28, 13 to 14, 18 to 17, and 6 to 5, separately, and connect lead 1、2 to power supply,the SMA wires (8)-(9)-(11)-(5)-(16)-(23)-(21)-(13) are actuated and the element [2]、[5]、[4]、[7] are in compressive stress state;If SMA wires (6)、(5)、(32)、(31)、(38)、(37)、(16)、(15) are damaged, short lead wire 27 to 28、31 to 32、17 to 20 separately, connect lead wires 5、8 to power supply, the SMA wires (11)-(33)-(36)-(46)-(45)-(23)-(22)-(12) are actuated, and 4 elements [4]、[7]、[10]、[13] are in compressive stress state,If a area is damaged, the relevant lead wires can be shorted and connected to power, (see figure 4) and relevant SMA wires can be actuated to improve the local stress state and prevent the damage extending.

system with good steadiness and anti-interference(e.g electrimagnetism, temperature and humidity).

The On-Line Detection System of Smart Composite Structure of Self-Adaptive Strength

1.The model of the system

Figure 6(a) shows the smart composite structure of self-adaptive strength, which consists of glass fiber and epoxy resin and in which optical fibers and SMA are embedded. The sample is a plate. Twenty optical fibers sensors are assumed arranged in two dimensional array on the plate. There are 10 sensors in each direction with equal separations between optic-fibers of 0.1 meter. The diameter of the optical fiber covered with epoxy resin is 125 μ m. A laser diode is used as the light source and we couple its beam with a collimator, a 1/4 wave slice, a len and 20 optical fibers. We put the len, polarizator and photodiode whose diameter is 1.6 mm together so that it can change a light signal into a electrical signal in order to provide input for neural network.

On two surfaces of the plate, we stick the SMA foils which consist of many basic units and whose thickness is 0.3mm. While the composite structure is locally damaged (for example a bullet hit), the strain pattern in the structure and the outputs of the optic sensors near the damage area are changed, as a result the outputs of the photodiodes are varied. The sensors are connected to an optical and electronic interface that monitors the variation in sensor output produced by a varying strain. The optical intensity changes are converted into electical signals and input to a processor unit which processes in parallel by a artifical neural network. A 12 bits 20 channels 200 KHz A/D converter is used to acquire data from the optical and electronic interface. The data are used as the inputs of neural network and are processed in parallel. Figure 6(b) shows the sample.

For a particular input data from the sensor array, which offers the information about a damage. The brightest point at its desired spatial position is displayed on the screen of AST386 computer (shown in Fig 6(c)).

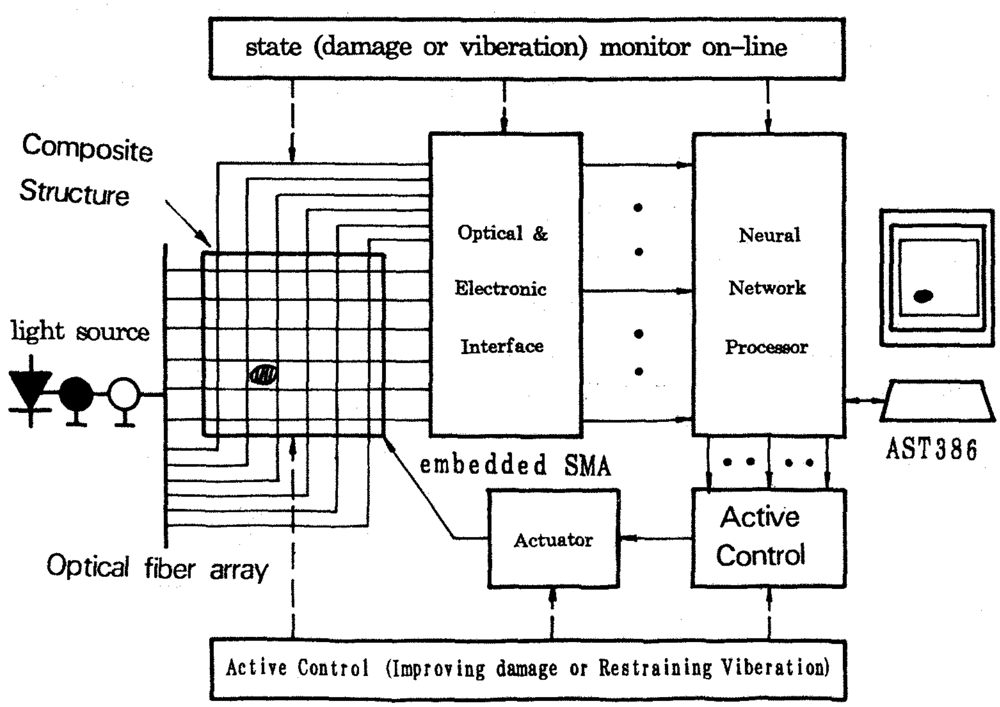


Figure 6(a) The system diagram of a smart structure of self-adaptive strength.

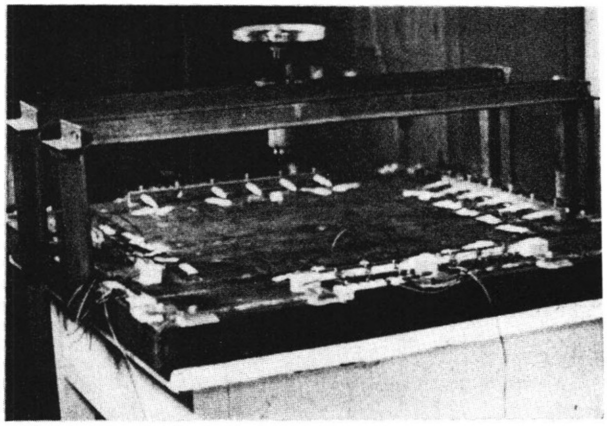


Figure 6(b) The plate with a optical fiber array.

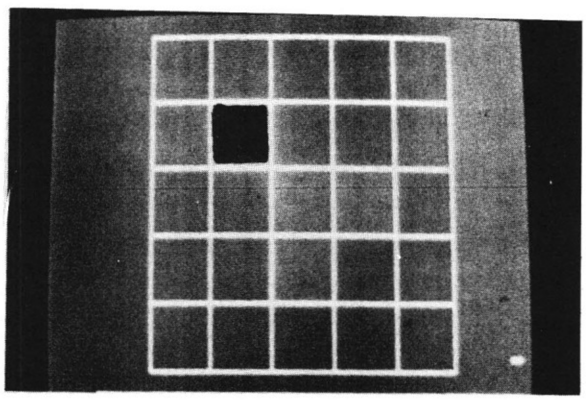


Figure 6(c) The damage positions displayed on the screen.

This brightest point in red colour reports the position of a damage area we want to determine. At the same time, the control board plugged in a AST386 computer sends out signals to actuate the SMA wries, so the rim of a damage will be in compressive strain state.

Figure 7 shows the distribution of resistance wires embedded in a smart composite structure of self-adaptive strength, which consists of glass fiber and epoxy resin and in which resistance strain wires and SMA are embedded. The resistance rate of a wire is 1000 Ω /m. The resistance wires and the SMA foils are symmetrically mounted on the both surfaces. The resistance wires are connected as half bridge and bridge voltage is 6v.

The test can be simulated in various loadings and boundary conditions such as fixed all round, cantilever etc.

2. The artificial neural network processor

The processor used for smart structure must process the output of the sensors and generate the appropriate control signals. When sensing and actuation may be distributed over large areas or consist of dozens to thousands of discrete elements, this task is computationally intensive and time consuming. Artificial neural

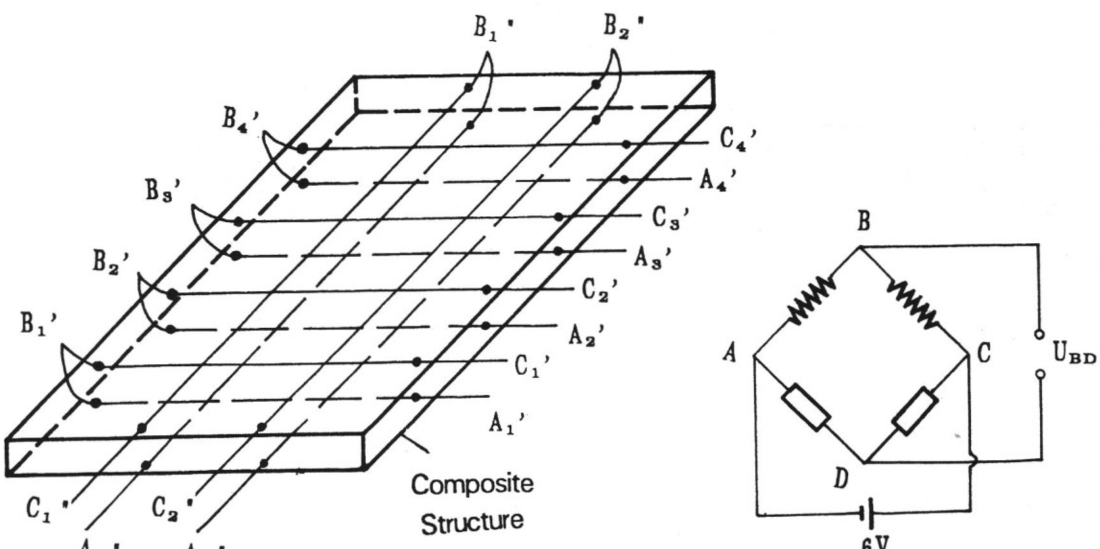


Figure 7. The diagram of resistance wires distribution.

networks offer an opportunity to implement a massively parallel computationally architecture capable of processing, in real time, multiple inputs and outputs. So it is suited for the on-line monitoring of smart structure[2][3][4].

A neural network was simulated and trained accomplished off-line by proprietary computer software.The weights between inputs and outputs are representative of the desired input-output relationship and are determined by the training process. A neural network processor is a three-layer back-propagation architecture which has a parallel structure. Once damage occurs in smart structures. A trained neural network processor automatically outputs the position of a damage and displays it on the monitor, so as to realize the health monitoring of the structural system on-line. An artificial neural network modeled based on the three-layer back-propagation network is shown in figure 8.

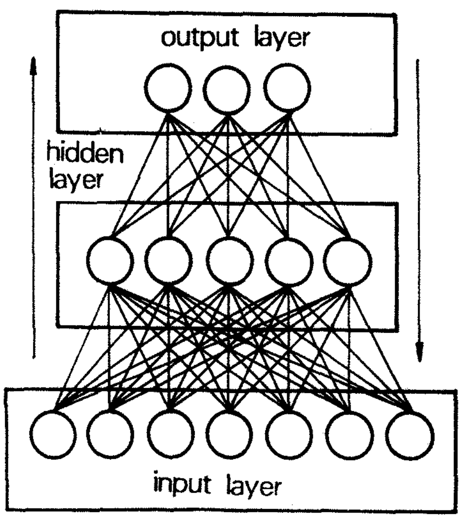


Figure 8. The model of a three-layer back-propagation neural network.

The input layer receives input patterns, usually does not have processing units in this layer, and simply transmits the signals faithfully to the next layer.The hidden layer consists of a certain number of processing units.And then the output layer constitutes the output channels, which also comprises the processing units.The input pattern is propagated forward and actual responses are obtained. The errors between the desired outputs and actual outputs propagate backward through the network,to provide a vital information for weight adaptation. The backpropagation algorithm delicately uses this information to adjust the weights so that a "mean-squared" error measure is minimized. This supervised learning algorithm,using a gradient descent optimization scheme, makes the network converge to a minimum in the weight space.

Supposing the number of input patterns is N, output nodes is K and desired accuarcy is e_{max},The following is the learning steps:

Step 1: produce the small initial random weight values.

$$0 < W_{ij} < 1, \quad i=0,1,\cdots\cdots,N-1$$
$$j=0,1,\cdots\cdots,K-1$$

Step 2: input a training sample and desired output

(Supposing the sample number is P)

$$X_p = [X_{p0}, X_{p1}, \cdots\cdots, X_{p(N-1)}]^{-1}$$
$$T_p = [T_{p0}, T_{p1}, \cdots\cdots, T_{p(K-1)}]^{-1}$$

compute the node outputs of hidden layer and output layer

$$O_{pj} = \frac{1}{1+e^{-net_j}}; \quad net_j = \Sigma W_{ji} X_{pj} - \theta_j$$
$$O_{pk} = \frac{1}{1+e^{-net_k}}; \quad net_k = \Sigma W_{kj} X_{pj} - \theta_k$$

where θ_j, θ_k are the threshold.

Step 3: calculat the mean-squared system error which is defined by

$$E = \frac{1}{2P} \Sigma \Sigma (t_{pk} - O_{pk})^2$$

where P is the number of the training patterns.

Step 4: test the convergent criteria. The training procoss stops if $E < e_{max}$ is satisfying. If not, continous

Step 5: update the Weights

$$\delta_{pj} = O_{pj}(1-O_{pj}) \sum_k \delta_{pk} W_{kj}$$
$$\delta_{pk} = (t_{pk} - O_{pk}) O_{pk} (1-O_{pk})$$
$$\Delta W_{ji}(n+1) = \eta(\delta_i O_i) + \alpha \Delta W_{ji}(n)$$

where η is called a learning rate, which is used to control the convergent speed of a learning process, and α is called a monentum term.

Step 6: go to step 2

After trained,the fixed weight distribution of a whole network becomes the representation of the relationship between strain patterns and damage locations. When an unknown input is measured, the neural network can calculate the strain in real-time because neural network operates in parallel and has self-learning and self-orgainzing properties.

3.Experiment results and discussion

The number of input elements of a neural network depends on the number of sensors (optical fibers or strain gauges) embedded. In this case there are 8 input elements, and we choose only 4 sensors in each direction which are located near the centre.The outputs of the neural network are the location codes which represent the 9 areas on the smart structure. When a damage occurs(supposing number i,$1<i<9$),the output Yi becomes greater than 0.9, and the number i in the network in red colour is displaied on the monitor, which represent the damage location in the structure. Moreover,the SMA embedded in the structure are actuated, so the rim of the damage bears compressive strain.The 30 sets of training data are prepared corresponding to the 30 selected damage locations on the smart structure, and each of them is represented by the corresponding strain pattern from the embedded opticfiber sensor array or strain gauge array.

Each set of inputs had 8 values corresponding to the 8 sensor array outputs. Table 1 shows the learning date of $8\times10\times9$ BP network.

This system has been modeled and simulated with the PDP system which consists of TMS320C25 and AST386 computer.The neural networks are simulated and trained accomplished off-line by proprietary computer software which is programed with Turbo C2.0.

The training process starts with the learning rate $\eta=0.7$,momentum term $\alpha=0.9$, and the weights are optimized with reprect to the whole input pool at 869 interations with the mean-squared system error E less than 0.0001. After trained, the fixed weight distribution of the entire network becomes the representation of the relationship between strain patterns and damage locations.

The simulation results in 100% of the training inputs are correctly classified into desired clusters.The trained neural network is tested by using untrained damage inputs. We pick 15 sets of untrained inputs,which correspond to 15 damage locations different from the trained inputs. The test results show that all of the untrained inputs are correctly classified to the closest cluster.

The trained neural network processor is also tested with a noisy input. The noise values are 15% with respect to the training inputs.The results show that all trained damage inputs with noise are still associated with their desired clusters, which means that the processor operates normally.

Table 2 shows the simulation experiment data and results of $8\times10\times9$ BP network on-line.

Table 1.

input x1 … x8	output y1 … y9	input x1 … x8	output y1 … y9
0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0 0	0 1 1 1 0 1 1 0	0 0 0 0 1 1 0 0 0
0 0 0 0 0 0 0 1	0 0 0 0 0 0 0 0 0	1 1 1 1 0 1 1 0	0 0 0 1 1 1 0 0 0
1 1 0 0 1 1 0 0	1 0 0 0 0 0 0 0 0	1 1 1 0 0 0 1 1	0 0 0 0 0 0 1 1 0
0 1 1 0 1 1 0 0	0 1 0 0 0 0 0 0 0	0 1 1 1 0 0 1 1	0 0 0 0 0 0 0 1 1
0 0 1 1 1 1 0 0	0 0 1 0 0 0 0 0 0	1 1 1 1 0 0 1 1	0 0 0 0 0 0 1 1 1
1 1 0 0 0 1 1 0	0 0 0 1 0 0 0 0 0	1 1 0 0 1 1 1 0	1 0 0 1 0 0 0 0 0
0 1 1 0 0 1 1 0	0 0 0 0 1 0 0 0 0	1 1 0 0 0 1 1 1	0 0 0 1 0 0 1 0 0
0 0 1 1 0 1 1 0	0 0 0 0 0 1 0 0 0	1 1 0 0 1 1 1 1	1 0 0 1 0 0 1 0 0
1 1 0 0 0 1 1 0	0 0 0 0 0 0 1 0 0	0 1 1 0 1 1 1 0	0 1 0 0 1 0 0 0 0
0 1 1 0 0 0 1 1	0 0 0 0 0 0 0 1 0	0 1 1 0 0 1 1 1	0 0 0 0 1 0 0 1 0
0 0 1 1 0 0 1 1	0 0 0 0 0 0 0 0 1	0 1 1 0 1 1 1 1	0 1 0 0 1 0 0 1 0
1 1 1 0 1 1 0 0	1 1 0 0 0 0 0 0 0	0 0 1 1 1 1 1 0	0 0 1 0 0 1 0 0 0
0 1 1 1 1 1 0 0	0 1 1 0 0 0 0 0 0	0 0 1 1 0 1 1 1	0 0 0 0 0 1 0 0 1
1 1 1 1 1 1 0 0	1 1 0 0 0 0 0 0 0	0 0 1 1 1 1 1 1	0 0 1 0 0 1 0 0 1
1 1 1 0 0 1 1 0	0 0 0 1 1 0 0 0 0	1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1

Table 2.

input x1···x8	output y1···y9
0.9 0.9 0.1 0.1 0.9 0.9 0.1 0.1	.99 .01 .01 .01 .00 .00 .00 .00 .00
0.1 0.1 0.9 0.9 0.1 0.9 0.9 0.1	.00 .00 .01 .00 .01 .99 .00 .00 .00
0.9 0.9 0.1 0.1 0.1 0.1 0.9 0.9	.00 .00 .00 .01 .00 .00 .99 .01 .00
0.9 0.9 0.9 0.1 0.9 0.9 0.1 0.1	.99 .98 .01 .01 .01 .00 .00 .00 .00
0.9 0.9 0.9 0.9 0.9 0.9 0.1 0.1	.98 1.0 1.0 .00 .00 .00 .00 .00 .00
0.1 0.9 0.9 0.9 0.1 0.9 0.9 0.1	.00 .00 .00 .01 1.0 .99 .00 .00 .00
0.9 0.9 0.9 0.9 0.1 0.1 0.9 0.9	.00 .00 .00 .00 .00 .00 1.0 1.0 1.0
0.9 0.9 0.1 0.1 0.9 0.9 0.9 0.1	.98 .00 .00 .98 .00 .00 .00 .01 .00
0.1 0.9 0.9 0.1 0.9 0.9 0.9 0.1	.00 .99 .00 .00 .99 .00 .00 .00 .00
0.1 0.9 0.9 0.1 0.1 0.9 0.9 0.9	.00 .01 .00 .00 .98 .01 .00 .99 .01
0.1 0.9 0.9 0.1 0.9 0.9 0.9 0.9	.00 1.0 .00 .00 1.0 .00 .00 .99 .00
0.1 0.1 0.9 0.9 0.9 0.9 0.9 0.1	.00 .00 .98 .00 .00 .98 .00 .00 .00
0.1 0.2 0.9 0.9 0.1 0.9 0.9 0.9	.00 .00 .01 .00 .00 .98 .00 .01 .99
0.2 0.1 0.9 0.9 0.9 0.8 0.9 0.9	.00 .00 1.0 .01 .00 1.0 .00 .00 .98
0.9 0.9 0.9 0.9 0.9 0.9 0.9 0.8	.99 .99 .98 .99 .98 .99 .99 .99 .99

In the study of feed forward multi-layers neural network, we adjust the number of nodes of the hidded layer continuously. The results show that the number of interation is least, when the number of nodes of hidden layer is equal to ten, and the learning time is prolonged with the increasment of learning samples. Sometime, the local minimum will reach.

To the network with connect weights N, when learning in the series computer, the time complex of BP algorithm is $O(N^3)$. When learning in the parallel computer, the time complex is $O(N^2)$ and the learning samples are $O(N)$. In order to save learning time, it is better to learn in a parallel computer. On the other hand, the choice of η must be attended. Generally the efficiency of learning is increased when η is bigger, but it may cause oscillation.

The experiment results show that the smart structure, in which we use optic-fibers or resistance strain wires as sensing neural, SMA as control parts, has advantage of on-line health monitoring. The system operates well.

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