Locating and classifying defects using an hybrid data base

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Abstract. A computational inverse technique was used in the localization and classification of defects. Postulated voids of two different sizes (2 mm and 4 mm diameter) were introduced in PMMA bars with and without a notch. The bar dimensions are 200x20x5 mm. One half of them were plain and the other half has a notch (3 mm x 4 mm) which is close to the defect area (19 mm x 16 mm). This analysis was done with an Artificial Neural Network (ANN) and its optimization was done with an Adaptive Neuro Fuzzy Procedure (ANFIS). A hybrid data base was developed with numerical and experimental results. Synthetic data was generated with the finite element method using SOLID95 element of ANSYS code. A parametric analysis was carried out. Only one defect in such bars was taken into account and the first five natural frequencies were calculated. 460 cases were evaluated. Half of them were plain and the other half has a notch. All the input data was classified in two groups. Each one has 230 cases and corresponds to one of the two sort of voids mentioned above. On the other hand, experimental analysis was carried on with PMMA specimens of the same size. The first two natural frequencies of 40 cases were obtained with one void. The other three frequencies were obtained numerically. 20 of these bars were plain and the others have a notch. These experimental results were introduced in the synthetic data base. 400 cases were taken randomly and, with this information, the ANN was trained with the backpropagation algorithm. The accuracy of the results was tested with the 100 cases that were left. In the next stage of this work, the ANN output was optimized with ANFIS. Previous papers showed that localization and classification of defects was reduced as notches were introduced in such bars. In the case of this paper, improved results were obtained when a hybrid data base was used.
1. Introduction

The development of Artificial Neural Networks (ANN) began a few decades ago and its application in different areas of knowledge has increased over the years. As example, it can be mentioned fault detection, geological prediction, design of expert systems, to name a few. The ANN, such as perceptors, unlike other numerical methods, does not use sequential calculation algorithms. On the contrary learning or the algorithm solution is a parallel calculation.

In the case of localization of defects, ANN is useful for this purpose. It has been proposed that the dynamic response of a body depends on its geometry. Therefore, when a defect is introduced, the natural frequency varies [1].

This idea has been used in conjunction with the Finite Element Method, following an Inverse Computation Analysis. Defects are commonly localized by evaluating the mechanical response of a structure. In the open literature, there are reported cases in which the vibration response is used in this indirect approach. Therefore, defects are localized and classified by calculating the natural frequencies with the Finite Element Method for determining them experimentally in conjunction with ANN. Neuro fuzzy logic can be used in the optimization of the analysis.

In a previous papers [2, 3, 4, 5, 6], the dynamic response has been used for this purpose. The propagation of elastic waves was considered in [2]. Another alternative was evaluated in [3]. In this case, the input data was the dynamic strains measured at the boundary of the bar. The approach, in which the dynamic response of the body with defects was evaluated the natural frequencies, was followed in [4, 5, 6]. Although several attempts have been tried, the improvement of the evaluation is not straightforward. This process is heuristic and it is not possible to establish clear outlines at this respect.

In accordance with previous experiences, ANN gives a good localization of the defects when the natural frequencies are used to generate the input data. Neuro fuzzy analysis can be used for the optimization of the solution. For the purpose of this work, it is proposed to use the same approach. The results were accurate when the geometry of the dominium of analysis is simple. Nonetheless, as it becomes more complex, such accuracy is reduced. It is important to mention that in the previous works mentioned above, synthetic data was used mainly. It is the interest to increase the precision of the results obtained. For this reason, in present analysis, reduced experimental information is introduced in the input data base in order to see the impact on the convergence of the results. The consistency of this approach will be analyzed by introducing some changes in the geometry of the component analyzed.

2. Statement of the problem

The purpose of this neuro-fuzzy analysis is the localization and classification of defects, using a hybrid data base, in the bars shown in figure 1. In both cases, the thickness is 5 mm. A defect was located in the shadowed area (18 mm x 16 mm), which is located 1 mm away from the bar sides. Two types of defects were considered. They have 2 mm and 4 mm diameters. This arrangement was selected in such way that the voids may be considered as through thickness defects. In order to evaluate the robustness of the neuro fuzzy model, two cases were considered: (1) a plain bar and (2) a bar with a notch of 3x4 mm. In the last case, the defect zone and the notch are closed.
3. Numerical Analysis

3.1 Finite Element Analysis. A parametric analysis was done, through a macro procedure, in order to create the synthetic data. In this way, the first five natural frequencies were calculated when only one defect is located in the shadowed area of figure 1. This was done with ANSYS 11.0 code. 460 cases were run for each sort of bar. This data was classified in two groups. Each one corresponds to the type of the postulated defects (D2 mm and D4 mm). 230 cases are within each group.

The finite element mesh has 2276 SOLID95 elements. It was developed with the automatic mesh generation algorithm with a relevance of six (figure 2). Each PMMA bar was clamped at its bottom. The modulus of elasticity of the material, Poisson ratio and density are 3.37 GPa, 0.3 and 1190 kg/m³, respectively. These data were obtained from the material manufacturer [7].

![Figure 1. Dimensions of the analyzed bar (A) Plain bar; (B) Notched bar.](image)

![Figure 2. Finite Element Meshes of the analyzed bars (A) Plain bar and (B) Notched bar.](image)

3.2 Experimental analysis. 20 PMMA bars for each case shown in figure 1 were manufactured. A SYSTEM 6200 was used as data acquisition system. The exiting device was an impact hammer KISTLER model 9728A2000. It was used in conjunction with a piezoelectric card model 6050, an accelerometer VISHAY 8632C10 and the STRAINSMART code. A schematic arrangement of the experimental set up is shown in figure 3. The first two natural frequencies for each proposed case were evaluated.
In order to complement the input data, the natural frequencies 3, 4 and 5 were calculated numerically. All the data obtained in this way was mixed with the synthetic which was previously described.

3.3 ANN Analysis. The ANN analysis was done with MATLAB 6.5. As it was mentioned before, the input data contains the first five natural frequencies, obtained experimentally and numerically. The output data are the coordinates X and Y of the defects and a number that classified the type of defect. The origin of the coordinate system is shown in figure 1. In this way, all the points in the bar have positive coordinates. All the data was normalized between 0-1.

In the case of the plain bar and notched bar, axix layers ANN (25-20-15- 10-5-3) gave best results in both cases. All the layers have log neurons. Training was done with backpropagation, following the TRAINSCG procedure. 50000 epochs were required. 400 cases were taken randomly in order to train the proposed Neural Network and the accuracy of the localization and classification of the defects was assessed with the other 100, which were left.

One has to keep in mind that these networks give continuous results. Consequently, the criteria of the defect classification are 0 and 1 for D4mm and D2mm, respectively. The tolerance range that was considered for the first type of defect is 0 to 0.10 and for the second type of defect, it was 0.9 to 1.0.

3.4 Neuro Fuzzy Analysis. A neuro fuzzy system is proposed to improve the results previously obtained with the ANN analysis. This technique provides a method for the development of models which relates input and output data. In this procedure, a network with membership functions is proposed. The parameters of such functions are calculated with the training data. This learning method works similarly to that of neural networks. In this work, the fuzzy logic tool box of MATLAB 6.5 was used, following the ANFIS procedure. The optimization of the results, for both bars, was done with a network, which has 35 constant membership functions for X coordinates, 25 for Y coordinates; GBELL functions were used. Regarding the classification of defects, TRIMF functions were used. Training was done with 350 epochs for X coordinates and 200 for Y coordinates and classification.

3.5 Validation Analysis. In order to identify the error percentage among the analytical, experimental and numerical results, the first two natural frequencies of a plain bar were evaluated using a 2D plate theory. Results are summarized in table 1.

| Table 1. Error percentage for analyticial, experimental and numerical evaluation |
|-----------------------------------|-----------------|-----------------|
| Analytical value | Percentaje of desviacion for experimental value | Percentaje of desviacion for numerical value |
| 34Hz | 1.5% | 0.84% |
| 1.8% | 0.23% |
Differences between analytical, experimental and numerical results are minimum. The first two natural frequencies of all the cases analyzed are in this range. Therefore, it can be said that this analysis validate the used for this purpose.

4. Analysis of the results

4.1 Plain Bar Analysis with an ANN. In the evaluation of the results related with the localization of defects, an accuracy range of ±5% was considered. Under this condition, 45 X coordinates and 97 Y coordinates were localized. Besides, all defects were classified. As an illustration purpose, ten points of the assessment data were taken randomly. Figure 4 compares the estimated and the real coordinates. The classification of the defects is shown in figure 5.

4.2 Plain Bar Analysis with ANFIS. In order to improve the evaluation of the X coordinate, the ANN output was fed to the Adaptive Neuro Fuzzy Interference System (ANFIS). When a ±5% accuracy range was considered, 57 X coordinates and all Y coordinates were localized. All the defects were classified.

Figure 4. Comparison of 10 points taken randomly from the assessment data (plain bar)

Figure 5. Defect classification (plain bar)

The analysis of the absolute errors obtained in the estimation of X coordinate with ANN, shows that maximum value obtained is 17 mm. Only one case was found. This situation is improved with the neuro fuzzy analysis, because this parameter is reduced (8.4 mm). Six cases were found around this figure. In general terms, the localization average error, using ANN, is less than 3.3 mm. In relation with neuro fuzzy analysis, the average error is lower than 1.8 mm. Regarding Y coordinate; the maximum absolute error is 2.31 mm. One has to keep in mind that the longest side of the zone, in which the defects are located, is parallel to the Y axis. The absolute error of ten defects taken randomly is shown in figure 6.
4.3 Notched Bar Analysis with an ANN. The obtained results were evaluated with an accuracy range of ±5%. Under this condition, 51 X coordinates were localized. In the case of Y coordinates, 97 of them were localized. Moreover, all defects were classified. Figure 7 compares the estimated and the real coordinates of ten cases taken randomly. The classification of the defects is shown in figure 8.

4.4 Notched Bar Analysis with ANFIS. Initially, the results obtained were evaluated within an accuracy range of ±5%. 70 X coordinates were located. In the case of Y coordinates, all of them were localized. All the defects were correctly classified.
The analysis of the absolute errors shows that 16 mm is the maximum value in the estimation of X coordinate with ANN. This is the case of one point. Alternatively, 3.97 mm was the maximum error in the neuro fuzzy analysis. Four points were around this value.

Regarding Y coordinates, the maximum error is 8.5 mm in the ANN analysis. This is the case of one point. This situation is enhanced in the neuro fuzzy analysis. 7.5 mm was the maximum error. Four points are around this value. Figure 9 illustrates the absolute error for ten points taken randomly.

![Figure 9. Absolute error for ten points taken randomly](image)

5. Discussion

In order to define a guide line for future analysis, a comparison with previous results is shown in Table 2. It is important to observe that the geometry and the zone of the defects are similar in all these cases. In a preliminary paper [3], it was shown the ANN analysis is useful in the localization of postulated defects. However, as the geometry of the dominium of analysis becomes more complex, the accuracy of the estimations is reduced. The next step was the optimization of the results. This was done with ANFIS [4]. Some noise was included in the input data base used, and the evaluations were robust. However, the accuracy of the estimations was reduced in some degree [6]. At this point, it was important to improve the estimations when the geometry of the dominium of analysis becomes more complex.

It was decided to include some experimental data. Its inclusion improved the estimation of the neuro fuzzy analysis in the case of the notched bar. In the case of the plain bar, it can be said that the results are in the same range. Table 2 shows the evolution of the analysis developed. Encouraging results have been obtained. However, as the process is heuristic, more analysis is required in order to establish definitive conclusions.
Table 2. Comparison with previous results

| Data                        | ANN  | Neuro fuzzy Analysis | Reference |
|-----------------------------|------|----------------------|-----------|
| Plain bar (Synthetic data base) |      |                      |           |
| X Coordinate                | 71   | 87                   | 3         |
| Y Coordinate                | 100  | 100                  |           |
| Classification              | 99   | 100                  |           |
| Notched bar (Synthetic data base) |      |                      |           |
| X Coordinate                | 59   | 86                   | 3         |
| Y Coordinate                | 32   | 61                   |           |
| Classification              | 82   | 100                  |           |
| Bi-notched bar (Synthetic data base) |      |                      |           |
| X Coordinate                | 64   | 85                   | 5         |
| Y Coordinate                | 45   | 77                   |           |
| Classification              | 83   | 34                   |           |
| Plain bar (Hybrid data base) |      |                      | In this paper |
| X Coordinate                | 45   | 57                   |           |
| Y Coordinate                | 97   | 100                  |           |
| Classification              | 100  | 100                  |           |
| Notched bar (Hybrid data base) |      |                      | In this paper |
| X Coordinate                | 51   | 70                   |           |
| Y Coordinate                | 97   | 100                  |           |
| Classification              | 100  | 100                  |           |

6. Conclusions

In the development of this work, the results obtained in the localization and classification of defects with ANN, were compared with those obtained with ANFIS. In all cases, neuro fuzzy analysis gave better results. Besides, as the geometry of the dominion of interest becomes more complex, the accuracy of the results is reduced. This situation was observed when one or two notches were introduced.

In previous works [2-6], the same methodology was followed and synthetic data was only used. In this works few experimental results were introduced. An improvement of the results was observed, when the geometry is more complex. Therefore, the use of hybrid data base gave good results in localization and classification of defects. This kind of analysis provides new guide lines in the analysis of complex geometries. So, it is possible uses this kind of analysis in the evaluation of machinery elements.

Acknowledgements

The support given by the IPN, COFAA, TESCo and CONACyT for the development of this work is kindly acknowledged.

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