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Sensor fusion of a railway bridge load test using neural networks

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Abstract

Field testing of bridge vibrations induced by passage of vehicle is an economic and practical form of bridge load testing. Data processing of this type of tests are usually carried out in a system identification framework using output measurements techniques which are categorized as parametric or nonparametric methods. These methods are based on the theory of probability. Learning theory which stems its origin from two separate disciplines of statistical learning theory and neural networks, presents an efficient and robust framework for data processing of such tests. In this article, the linear two layer feed forward neural network (NN) with back propagation learning rule has been adapted for strain and displacement sensors fusion of a railway bridge load test. The trained NN has been used for structural analysis and finite element (FE) model updating.

Keywords: Learning theory; Neural networks; Sensor fusion; Railway bridge; Lad test; Model updating

Article Outline

1. Introduction

Load testing of bridges is usually performed for structural health monitoring, diagnostics, damage detection, load rating, condition assessments, load carrying capacity estimation and model updating. Increasing attention to predictive maintenance and health monitoring of existing structures, has prompted more research work in this field. Health monitoring and system identification from responses of a bridge under passage of vehicles is an economical and practical type of bridge load testing (Peeters, 2000). Classical approach to data processing of this type of test is to use parametric and nonparametric system identification techniques which are based on probability theory (Sohn et al., 2003). Learning theory which is developed in two distinguished disciplines of statistical learning theory and neural networks provides an efficient and robust alternative method for data processing of above mentioned tests (Bridge Diagnostics Inc., 2003). Artificial neural networks have recently been used for data analysis of such tests in different type of structures ([Cao et al., 1998] , [3] and [7]).

In this article, a linear two layers feed forward NN with back propagation learning rule is used for strain and displacement sensors fusion. The trained NN is used for structural analysis, finite element model updating and influence line estimation of a railway bridge.

2. Bridge description

Neka through truss bridge spans over Neka River. The bridge is located in north district of the railway network of Iran. It is located 300 m far from Neka station in Mazandaran province.

The bridge has a 36 m span and has been constructed using steel members. The two side trusses consist of 12 bays of equal length. The height of each truss is 3.3 m and the distance between two trusses is 5.5 m. The bridge provides the passage of one railway track (see Fig. 1).

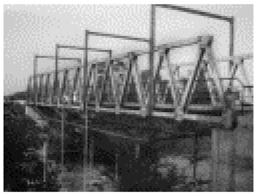 Full-size image (42K)

Fig. 1.

Neka through truss bridge.

Top and bottom chords and vertical bracings are made of IPBL220 sections, but chords are strengthened with four *L*80×65×8 mm angles and two 160×10 mm plates. The chords and vertical bracings are connected to each other through a gusset plate at each node using bolts. The truss has 13 floor beams which are made of IPBL400 sections. Two stringers which are simply connected to floor beams complete the deck structure. The stringers are made of IPBL240 sections and located at a 1.5 m distance from each other. The UIC60 rails are directly seated and fastened to the stringers. The track is without ballast and traverse.

3. Test instrumentation

Eighty-nine sensors were installed at different locations of the Neka bridge for the purpose of load test (Mohammadzadeh, 2004). The sensors composed of 42 strain gauges, 20 displacement transducer (LVDT) and 27 accelerometers.

The strain gauges were installed on different members as follows: 12 numbers on stringers, 7 numbers on floor beams, 6 numbers on vertical bracings and 16 numbers on top and bottom chords. The length of each strain gauge was 5 mm.

The 5–100 mm displacement transducers (LVDT) were mounted using magnet stands on the scaffoldings which were erected to provide suitable support. The LVDTs had 0.1% accuracy.

Accelerometers of 2 and 5 g with 0–400 Hz band of frequency were used for vertical and lateral acceleration measurements. The accuracy of accelerometers was 0.25%.

Ninety-six channels static data logger and a 48 channels dynamic one were used for data gathering. Sampling frequency of static and dynamic data loggers was 20 and 2000 Hz, respectively.

4. Loading

Passage of vehicle over the bridge with various speeds was considered for bridge loading. A single locomotive and a locomotive with two freight wagons were used for this purpose (Table 1). The locomotive had six axle and 111 tones weight. It was manufactured by General Motors Company. Each freight wagons had four axles and 76 tones weights (Fig. 2).

Table 1. Locomotive and freight wagon description

Vehicle	Length over buffers (m)	Axle spacing (m)	Center to center of trucks (m)	Weight (ton)	Number of axles
Locomotive GT26	21.1	1.69–2.02	12.5	110.97	6
Freight wagon	15.06	1.8	9.86	76	4


Full-size image (37K)

Fig. 2.

Passage of locomotive with two freight wagons.

The strain, displacement and acceleration time history of the structural elements of the bridge, due to passage of the locomotive or locomotive with two freight wagons were measured. The speed of passage of the vehicle varied from crawling to 55 km/h. Data gathering was done using static and dynamic data loggers. The maximum amount of load superimposed on the bridge deck was 111 tones under the passage of single locomotive and, but it reached 208 tones under the passage of locomotive and two freight wagons.

5. Input estimation

Design of the test and placement of the sensors was performed in such a way that the moving load of the vehicles could be estimated from sensor measurements. The strain time history of the stringers near their supports was a good mean for load identification. The strain history of stringer support at the middle bay of the deck under passage of a single locomotive and locomotive with two freight wagons is shown in Fig. 3 and Fig. 4, respectively. As observed from the figures, the location of axles can be clearly distinguished.

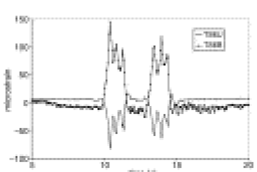
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Fig. 3.

Strain history of stringer support at the middle bay of the deck under passage of a single locomotive.

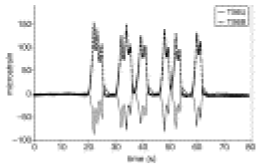 Full-size image (20K)

Fig. 4.

Strain history of stringer support at the middle bay of the deck under passage of locomotive with two freight wagons.

Based on above, loading time history of the passing vehicle was estimated from three strain time histories of strain gauges installed at the beginning, middle and end of the bridge. Therefore, 73 loading time history of the bridge along the deck with equal distance of 50 cm were estimated. Fig. 5a shows estimated loading time history at the first and last node of the bridge under passage of a single locomotive and Fig. 5b shows estimated loading time history at the middle of the bridge under passage of a locomotive with two freight wagons.

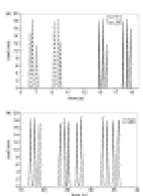 Full-size image (38K)

Fig. 5.

(a) Input load identification at the first and the last (73th) node (passage of single locomotive with speed of 15 km/h). (b) Input load identification at the middle node (37th) (passage of locomotive with two wagons with speed of 5 km/h).

6. NN representation of FE model

NN can be used for modeling of input and output relation of FE model. If all degrees of freedom of FE model which contribute to loading are considered as input layer and the responses of the FE model are considered as output layer, a linear feed forward two layers NN can find linear relation between input and output of FE model. If distribution of load between degrees of freedom of FE model is considered as distribution of load between input layer neurons, the weight matrix of the NN model is the same as flexibility matrix of the FE model.

The advantage of NN representation of the FE model is learning ability. This ability can be used for estimation of flexibility matrix from result of field test.

7. FE modeling of the Neka Bridge

FE modeling of the Neka Bridge was done according to As Built conditions of the structure. Top and bottom chords and vertical bracings were modeled using axial members. The stringers and floor beams were modeled using beam elements. Connections of top and bottom chords and vertical bracings to each other and stringer connections to floor beams were modeled as simple joints. Floor beam connections to bottom chord were assumed as rigid joints (Fig. 6).

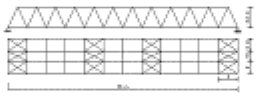 Full-size image (4K)

Fig. 6.

Finite element model of the Neka Bridge.

8. Sensor fusion with NN

Two layer linear perceptron feed forward NN with back propagation learning algorithm was used for sensor fusion of the Neka Bridge. As the relation of loading to strain and displacement responses of the bridge was linear, a NN model without hidden layer was considered.

A NN with 73 neuron in input layer and 42 neuron in output layer was considered for strain and displacement sensors fusion. Imposed loading of the bridge at every 50 cm along the deck were considered in input layer. Loading was estimated from local strain time history response of the bridge.

Twenty-two strain time histories of top and bottom chords and 20 displacement measurements along the deck were selected as output layer of NN model.

The response of the bridge under passage of single locomotive with speed of 15 km/h was considered in the learning mode of NN. Fig. 7 compares the strain time history measurement of bottom chord at the 7th bay of the truss with the response of the NN model, the data had been used for training the NN. Therefore, the agreement between the two sets of results is not unexpected. Fig. 8 compares the strain time history measurement at the same location with the response of the NN model, under the passage of a locomotive with two freight wagon with the speed of 50 km/h. This experimental data was not used in training the NN. Fig. 9 compares the strain measurement of vertical bracing at the middle of the bridge with NN model. The test is the same as Fig. 8.

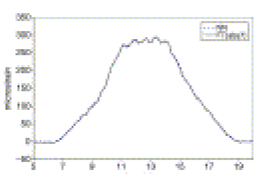 Full-size image (16K)

Fig. 7.

Comparison of the measured strain of bottom chord at the seventh bay with NN, under the passage of locomotive (*V*=15 km/h).

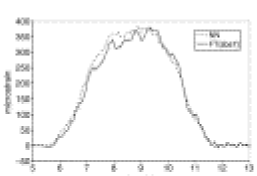 Full-size image (15K)

Fig. 8.

Comparison of the measured strain of bottom chord at the seventh bay with NN, under the passage of locomotive with two wagons (*V*=50 km/h).

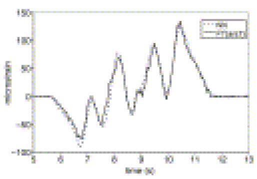
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Fig. 9.

Comparison of the measured strain of vertical bracing at the middle of the bridge with NN, under the passage of locomotive with two wagons (*V*=50 km/h).

Fig. 10 compares measured displacement at the middle of the bridge with NN model in the trained test similar to Fig. 7. Fig. 11 compares the measured displacement at the same location for a different vehicle arrangement and velocity which was not used for training the NN. Acceptable correlation exists between NN results and test measurements.

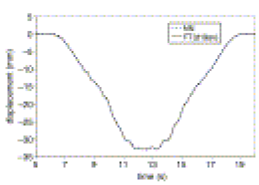
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Fig. 10.

Comparison of the measured displacement at the middle of the truss with NN, under the passage of single locomotive (*V*=15 km/h).

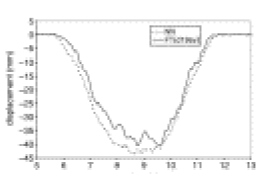
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Fig. 11.

Comparison of the measured displacement at the middle of the truss with response of NN, under the passage of locomotive with two wagons (*V*=50 km/h).

9. Application of trained NN

If a linear NN is used and all the loaded degrees of freedom of FE model are considered in input layer of NN model and the loads are distributed between input neurons with the same shape function of FE model, the weight matrix of neurons will be flexibility matrix of FE model at the trained degrees of freedom.

The trained NN model, not only has the ability of structural analysis, but also has the learning ability from field tests. Therefore, the trained NN can be used in finite element model updating and the elements of flexibility matrix can be estimated at the trained degrees of freedom. The resulting flexibility matrix will be a 73×42 one. Seventy-three being the number of applied load points and 42 being the number of selected measured responses. This matrix can be used in damage detection of structural elements. Fig. 12, Fig. 13 and Fig. 14 compare the variation of FE model and NN results for selected responses of the structure when a unit load is applied at different locations along the bridge. They are in fact graphic presentation of variation of the elements of three columns of the flexibility matrix.

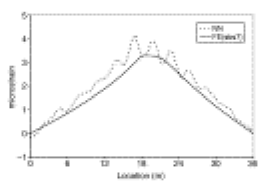
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Fig. 12.

Comparison of the identified strain flexibility matrix elements of bottom chord at the seventh bay of the truss with FE model.

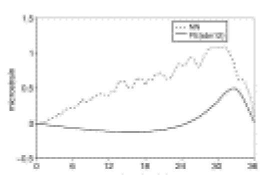
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Fig. 13.

Comparison of the identified strain flexibility matrix elements of bottom chord at the 12th bay of the truss with FE model.

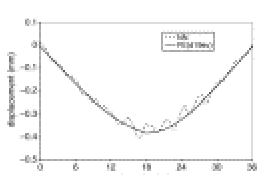
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Fig. 14.

Comparison of the identified displacement flexibility matrix elements of the middle of the truss with FE model.

In another form of presentation of the results, strain and displacement influence lines in trained degrees of freedom can be determined from NN model when a unit concentrated load is passing along the bridge. Fig. 15 shows the moving axle load along the bridge and Fig. 16 and Fig. 17 show strain and displacement response, respectively. With this application, the NN model is used as blind source separator and fundamental elements of the response (response to moving single axle) can be extracted from measured response (response to combination of moving axles).

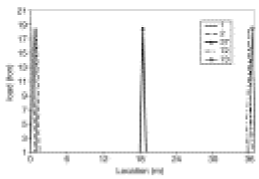

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Fig. 15.

Input loading of neurons of NN model for influence line calculation (moving single 18.5 tones axle).

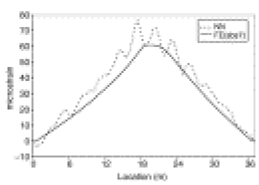

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Fig. 16.

Comparison of the identified strain response of bottom chord at the seventh bay of the truss with FE model under the passage of single 18.5 tones axle load.

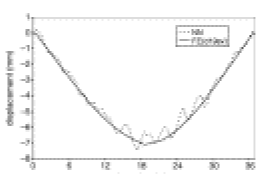

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Fig. 17.

Comparison of the identified displacement response of the middle of the truss with FE model under the passage of single 18.5 tones axle load.

On the other hand, the NN model may be considered as a structural analyzer as the response of the bridge at any trained degree of freedom to any arbitrary loading may be determined using the above information.

Another advantage of NN model is that higher order structural effects such as lateral stiffness of rods, *P*−*Δ* effects, stretching in shells and, etc. are automatically considered in NN models.

With this method, all sensor measurements of the field tests are being used for assessment of the structure and sensor fusion is effectively achieved and represented in a physical format (flexibility matrix).

10. Conclusions

The paper shows that if the loaded degrees of freedom of FE model is used as the input layer of NN model and the load distribution between degrees of freedom of FE model is the same as load distribution between input layer neurons, the weight matrix of NN model is the same as flexibility matrix of FE model at the trained degrees of freedom. Therefore, NN representation of FE model can be constructed. The NN model has the advantage of learning ability which can be used for structural system identification from the results of load tests.

As discussed, the NN can be used in data processing of the bridge load test due to passing of known vehicles. In this way, sensor fusion of measurements can be done and a structural analyzer can be constructed. Trained NN model can be used for finite element model updating (flexibility matrix identification) and influence line determination. The information may then be used in a later stage for the purpose of damage detection.

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