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THE APPLICATION OF NEURAL NETWORKS IN FORECASTING THE INFLUENCE OF TRAFFIC-INDUCED VIBRATIONS ON RESIDENTIAL BUILDINGS

ZASTOSOWANIE SZTUCZNYCH SIECI NEURONOWYCH W PROGNOZOWANIU WPŁYWU DRGAŃ KOMUNIKACYJNYCH NA BUDYNKI MIESZKALNE

A b s t r a c t

Traffic-induced vibrations may cause the cracking of plaster, damage to structural elements and, in extreme cases, may even lead to the structural collapse of residential buildings. The aim of this article is to analyse the effectiveness of a method of forecasting the impact of vibrations on residential buildings using the concept of artificial intelligence. The article presents several alternative forecasting systems for which it is not necessary to carry out laborious and costly measurement tests. The results show that artificial neural networks can be an effective tool for estimating the impact of traffic-induced vibrations on buildings; however, more cases need to be analysed in order to validate the system.

Keywords: traffic-induced vibrations, artificial neural networks, residential buildings

S t r e s z c z e n i e

Drgania komunikacyjne związane z ruchem drogowym mogą powodować w budynkach mieszkalnych zarysowania i spękania tynków, uszkodzenia elementów konstrukcji, a w sytuacjach skrajnych mogą prowadzić nawet do katastrofy budowlanej. Celem artykułu jest analiza efektywności metody prognozowania wpływu drgań na budynki mieszkalne przy wykorzystaniu idei sztucznej inteligencji. W artykule przedstawiono kilka alternatywnych systemów prognozujących wpływ drgań komunikacyjnych, w których nie jest konieczne przeprowadzanie pracochłonnych i kosztownych badań pomiarowych. Wyniki badań pokazują, że sztuczne sieci neuronowe mogą być dobrym narzędziem do prognozowania wpływu drgań komunikacyjnych na budynki, jednakże niezbędna jest większa liczba zbadanych przypadków dla uwiarygodnienia systemu.

Słowa kluczowe: drgania komunikacyjne, sztuczne sieci neuronowe, budynki mieszkalne

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1. Introduction

There are many causes of building vibrations, some of these are constant dynamic encumbrances, others are temporary [6]. The most common causes include: earthquakes [21, 22], mining tremors (paraseismic vibrations) [10, 11], large mechanical vibrating entities, air pressure, movement of large masses of people or vibrations resulting from vehicles/ trains using nearby roads/tracks [3, 14]. The last of these, often referred as traffic-induced vibrations, may cause the cracking of plaster, peeling of paint and loosening of plaster [3, 6]. Severe damage to structural elements or even construction disasters may also take place. The approximate distances of impact of vibrations on residential buildings are given in [5] as: 25 m from the centre of tram tracks and also the outer lane road; 40 m from the metro tunnel wall; 50 m from the centre of railway tracks. In addition to the impact of traffic-induced vibrations on buildings, the impact on people residing in buildings is also important [15]. This problem is particularly noticeable when people are exposed to prolonged vibrations and noise [5].

Many factors relating to the road upon which vehicles are driving and also the characteristics of the building may have an influence on the value of vibration. In order to determine the effect of traffic-induced vibrations on structures, relatively time-consuming and expensive measurements should be performed using specialised equipment. Conducting such measurements for all buildings located on a road may prove to be unprofitable from an economic point of view. Modern technology that is still evolving presents a number of possible solutions to these problems. One approach to diagnosing the impact of vibrations on a residential building is an expert system using artificial neural networks (ANNs) which is able to assess, with relatively high probability, the risk of the impact of vibrations without the necessity to perform measurements on a given building.

ANNs are widely used in civil engineering. Kuźniar & Chudyba used a neural network in forecasting the impact of vibrations of mining tremors on buildings [2, 9–11]. Another example of using this type of algorithm is the system described in [4] which uses the network to create ranking of bridges. The aim was to create a system which, based on several factors, would determine whether the bridge was in need urgent renovation. The authors were able to obtain satisfactory results and the system has been implemented in the General Directorate for National Roads and Motorways. Kogut in [8] applied ANNs in road problems based on [12], the aim of the study was to identify the critical time needed to cross a main road in Ohio. The author took various environmental, meteorological, ecological and social factors into account. The network correctly classified up to 87.5% correct responses with an acceptable error of 5%. The author of the study described in [8] also took into consideration the use of a network to determine the expected level of carbon monoxide air pollution within the vicinity of intersections in central Seattle. The network correctly described 70% of the values relative to the tested data. An ANN algorithm was also applied to assess the degree of technical wear of historical monuments (more in [20]).

As far as the authors are aware, ANNs have not yet been applied to estimate the impact of traffic-induced vibrations on buildings in relation to the standard [14] – this article presents the first such attempt. During the performance of tests, different measuring situations were classified according to specific criteria which were later applied to build a system based on ANN.

2. Studies of the influence of traffic-induced vibrations on buildings

A method of determining the impact of traffic-induced vibrations on buildings depends on the situation to be analysed. According to [5], four cases are possible:

- building designed but not yet built, the source of vibrations is predicted;
- building designed but not yet built, the source of vibrations is known;
- building already constructed, the source of vibrations is predicted;
- building already constructed, the source of vibrations is known.

In the first case, a computational model of the building is designed and the numerical analysis is performed, for example, by using the finite element method. In the second situation, ground vibration measurements are performed at the intended location. In the third case, vibrograms from a similar situation are applied. In the last case, the measurements of vibrations are performed, vibrograms are created, results are filtered and compared to the standard values [14].

Vibration studies are performed (see [5, 7, 14]) for short term loadings (occurring less than 3 minutes per day), long-term (occurring at least 3 minutes, maximum of 30 minutes per day) and regular (occurring above 30 minutes a day) to determine their influence upon the building. The analysis is then performed according to the standard [14]. Depending on the size of the vibrations, the resulting chart is located in one of the five zones of danger.

In this study, the vibration field measurements taken on four residential buildings are presented (Fig. 1). The source of vibrations was related to the movements of vehicles with varying tonnages and number of axles, travelling at different speeds. For each building, a series of several tests was conducted. As the outcome of the tests, after the analysis in 1/3 octave bands, authors received about 400 results for each building. The peak values were selected and plotted on Dynamic Influence Scale I graph (DIS I). Fig. 2 and Fig. 3 show examples of graphs of peak accelerations with respect to the centre frequencies. After performing an analysis consistent

Fig. 1. Buildings tested for traffic-induced vibrations (arrows indicate the locations of vibration sensors)

with [14], it was determined that three single-family houses fall into zone I (no impact of traffic-induced vibrations), and one of the buildings (no. 4) is in zone II (no impact on the design although there is a significant increase in the possibility of accelerated wear of plaster).

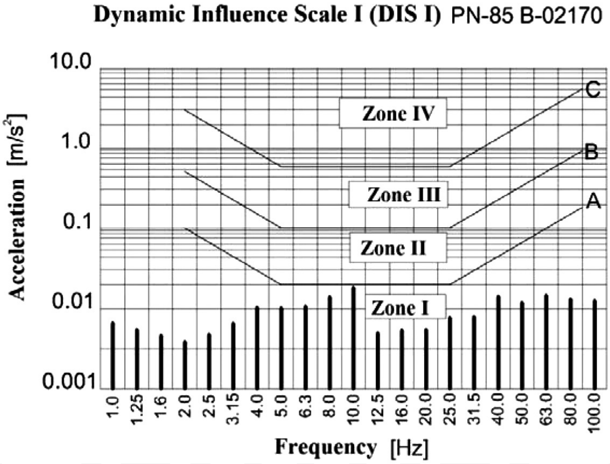

Fig. 2. Chart of peak accelerations with respect to the centre frequencies made for building no. 3 on the DIS I chart [14]

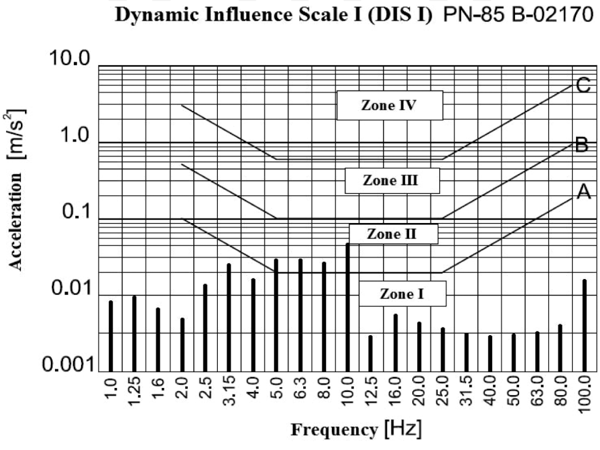

Fig. 3. Chart of peak accelerations with respect to the centre frequencies made for building no. 4 on the DIS I chart [14]

3. The application of artificial neural networks

The construction of the network was based on the principles described in [16, 18–19]. The first step was to create the database necessary to begin construction of an algorithm. The next step was to create the network itself. Factors that may affect traffic-induced vibrations

[3, 17] are: road type; road surface type; road surface condition; soil type; vehicle speed; weight of vehicles; vibration durability; shape and dimensions of building; distance from road; type of construction; basement; as well as possible natural, deliberate or accidental vibration-damping factors.

Eight networks were created in the *Matlab Neural Network Toolbox* program [13] using the back-propagation algorithm with the Levenberg-Marquardt learning algorithm. The group of training samples was selected which was submitted for the neural network. The field results obtained for this group were compared with the results obtained by the network (verification phase). In addition, prior to the completion of the network, testing samples were determined. These samples were not submitted to the network during the 'learning' stage. When the mean square error (MSE – see [1]) was satisfactory, the process of designing the network was completed [2, 16].

For each network considered in the study, the patterns were divided in the following way: 70% – learning samples, 15% – verifying samples and 15% – testing samples. Moreover, fourteen different factors were randomly taken into account in the networks. Eight different neural networks with one hidden layer were created – these were different from one another in the way in which they included different factors and in the number of neurons in the hidden layer (for each network – 1, 3, and 10 neurons were assumed).

The random combination of the following factors were taken into account: D_d – type of road; D_n – type of pavement; D_{sn} – state of road surface; D_p – speed of vehicle [km/h]; D_c – weight of vehicle [t]; D_d – sustainability of vibration; B_k – shape of the building; B_o – distance from road; B_r – year of construction; B_k – type of construction; B_p – basement; a_{xy} – peak acceleration in x and y orientations. On the output, the expected value was responsible for the information, whether the traffic-induced vibrations doesn't affect to the tested building (zone I according to DIS I [14]) or whether the impact is possible (zone II and higher). Therefore, the expected output value was equal to 0 or 1. Input vectors for the subsequent networks were assumed as follows:

- $X_{(6x1)} = \{D_d, D_n, D_{sn}, D_p, D_c, a_{xy})$
- $X_{(6x1)} = \{B_K, B_o, B_r, B_k, B_p, a_{xy})$
- $X_{(11x1)} = \{D_d, D_n, D_{sn}, D_p, D_c, B_K, B_o, B_r, B_k, B_p, a_{xy})$
- $X_{(8x1)} = \{D_d, D_n, B_K, B_o, B_r, B_k, B_p, a_{xy})$
- $X_{(6x1)} = \{D_d, D_n, B_K, B_o, B_r, a_{xy})$
- $X_{(5x1)} = \{D_d, D_n, D_{sn}, B_o, a_{xy})$
- $X_{(6x1)} = \{B_K, B_o, B_r, B_k, B_p, a_{xy})$
- $X_{(3x1)} = \{D_{sn}, B_o, a_{xy})$

After the learning network process in the *Matlab* program, the results shown in Table 1 were obtained. As a comparison of a network, MSE was calculated which shows the difference between the outputs achieved with the measurements and the results obtained by the action of the network. The results in Table 1 indicate that errors in the operation of an artificial neural network with different architecture and the established parameters are relatively small and do not exceed 3.92102×10^{-1} for the learning samples, 7.21951×10^{-1} for the validating samples and 3.00633×10^{0} for the testing samples. The smallest error of learning samples (1.15277×10^{-10}) was obtained for network no. 4 with the structure of 8–10–1. On the other hand, network no. 3, in which all parameters of the building and the road were taken into account, proved to be the least effective, since the error obtained was the largest and amounted to 1.21547×10^0 for verifying samples for the structure of 11–1–1.

4. Closing remarks

The purpose of this article was to present the results of the operation of an expert system based on artificial neural network activity which was applied to assess the impact of traffic-induced vibrations on buildings. Based on the analysis performed so far, we achieved a relatively low error value for artificial neural networks with different architecture and different established parameters. The obtained results are therefore promising and demonstrate the effectiveness of the system. It should be noted, however, that the actual database of results includes a relatively small number of different cases. Therefore, the next stage of research will be to perform measurements on a larger sample of residential buildings (at least 30 buildings are planned to be tested). The upgrading of the created networks, as well as checking other artificial intelligence algorithms, e.g. support vector machines, which can be also helpful in forecasting the impact of traffic-induced vibrations on buildings, will then be conducted. It is also planned to use different types of network [13] to compare the performance results.

Table 1

Characteristics of neural networks and errors of individual samples

No. of network and its architecture	MSE – training samples [–]	MSE –verification samples [–]	MSE – testing samples [–]
Network no. 1: 6-1-1	9.35191×10^{-9}	4.62128×10^{-1}	2.99485×10^{-2}
Network no. 1: 6-3-1	3.73315×10^{-1}	2.59167×10^{-3}	1.39104×10^{-2}
Network no. 1: 6-10-1	1.65689×10^{-4}	1.32041×10^{-6}	4.03857×10^{-1}
Network no. 2: 6-1-1	1.87873×10^{-1}	2.89750×10^{-1}	1.92824×10^{-1}
Network no. 2: 6-3-1	2.00448×10^{-4}	3.81108×10^{-1}	3.93508×10^{-2}
Network no. 2: 6-10-1	2.66272×10^{-5}	4.80413×10^{-2}	2.22438×10^{1}
Network no. 3: 11-1-1	1.83628×10^{-9}	1.21547×10^{0}	3.79064×10^{-1}
Network no. 3: 11-3-1	1.33541×10^{-1}	7.21951×10^{-1}	7.49835×10^{-1}
Network no. 3: 11-10-1	2.01744×10^{-1}	2.65415×10^{-2}	4.88491×10^{-2}
Network no. 4: 8-1-1	5.51261×10^{-2}	3.44147×10^{-1}	9.78215×10^{-3}
Network no. 4: 8-3-1	5.18379×10^{-5}	5.99858×10^{-1}	6.19752×10^{-1}
Network no. 4: 8-10-1	1.15277×10^{-10}	2.94855×10^{-1}	3.50704×10^{-3}
Network no. 5: 6-1-1	2.26650×10^{-1}	1.63530×10^{-1}	8.85599×10^{-2}

Network no. 5: 6-3-1	1.45447×10^{-1}	1.60828×10^{-2}	2.88384×10^{-2}
Network no. 5: 6-10-1	5.69944×10^{-2}	3.23589×10^{-3}	8.09436×10^{-3}
Network no. 6: 5-1-1	3.92102×10^{-1}	6.33194×10^{-2}	3.39044×10^{-2}
Network no. 6: 5-3-1	1.06009×10^{-1}	4.26290×10^{-2}	3.34781×10^{-2}
Network no. 6: 5-10-1	2.78595×10^{-3}	5.06962×10^{-4}	1.07499×10^{-2}
Network no. 7: 6-1-1	1.92296×10^{-2}	2.35511×10^{-1}	5.21189×10^{-2}
Network no. 7: 6-3-1	1.18251×10^{-2}	9.96684×10^{-1}	1.21119×10^{-1}
Network no. 7: 6-10-1	1.50109×10^{-1}	1.45799×10^{0}	3.00633×10^{-1}
Network no. 8: 3-1-1	7.40723×10^{-2}	2.76347×10^{-1}	1.01870×10^{-2}
Network no. 8: 3-3-1	6.62319×10^{-4}	1.44327×10^{-5}	1.75400×10^{-3}
Network no. 8: 3-10-1	4.88014×10^{-8}	4.79749×10^{-1}	4.47896×10^{-3}

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