Scientific Journal of the Military University of Land Forces
ISSN: 2544-7122 - print, 2545-0719 - online
2018, Volume 50, Number 3(189), Pages 144-154
DOI: 10.5604/01.3001.0012.6233

Original article

Vibration testing in buildings and safety of their operation

Anna Jakubczyk-Galczynska**, *Agata Siemaszko

Department of Metal Structures and Management in Civil Engineering, Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Poland,
annjakub@pg.gda.pl; agasiema@pg.gda.pl

INFORMATIONS

Article history:

Submited: 17 March 218

Accepted: 25 June 2018

Published: 30 September 2018

* Corresponding author

ABSTRACT

The paper presents the issue of vibrations in residential buildings located near roads. It describes the measurement methodology and criteria for assessing the impact of vibrations generated by passing trucks. The article specifies a method to establish the impact on the operation of the examined facilities and it promotes the idea of employing a Bayesian network to determine probabilistically the level of risk to single-family houses.

KEYWORDS

vibrations from road traffic, operation of buildings, Bayesian networks

Introduction

The significance of operational issues in buildings is underestimated, which is evidenced by failures and disasters that uncover to what extent the operational problems have remained unsolved or show the lack of forecasts anticipating such events. Decisions regarding the safe operation of a building may be taken intuitively, in which case they rely on the decision-maker's level of knowledge, or professionally, after obtaining expert opinions, which is a rare situation in Poland. Technical works are necessary to maintain the operational potential throughout the life cycle of a building and to ensure its safe and efficient use. The objective of operation management is to maintain the building in a functional or fit-for-use condition and to use it according to its intended purpose, which can be achieved by taking rational operational decisions. However, to be able to take such decisions, it is necessary to consider what factors affect the life cycle of a building. The influence exerted on the building by the environment represents one of these factors. Therefore, the authors concentrate in this paper on the issue of operational safety of buildings affected by the occurrence of vibrations caused by road traffic. Vibrations in buildings [Kuzniar 2002; Kuzniar and Waszczyszyn 2007] can be of seismic (among others, earthquakes) and also paraseismic origin, for example mining tremors, pile driving, sheet piling or traffic vibrations, discussed in this article.

1. Occurrence of vibrations from traffic

1.1. Influence of vibrations on the operation of a building

Preparation and operational expertise are of particular importance in the process of concept development and construction of building structures, when their operational properties are conceived, which can be only partially corrected at the designing stage. One of the aspects that is worth considering is the influence of vibrations on a building. The methodology for assessing the said influences is described in detail in the Polish standard [PN-B-02170:1985].

The occurrence of a permanent and long-lasting dynamic influence may result in severe damage to the structural members of the building or even in its failure. Other, less serious consequences include scratches, plaster cracks and paint falling off. To minimise the effects of traffic vibrations the following methods are employed: inserting elastic mats between the soil and the building, applying a bitumen layer on the road, eliminating rain water gullies, manhole covers and joints from the traffic lanes, reducing speed limits and maximum authorised mass and also increasing distances between buildings and roads [Hunaidi 2000].

Despite the awareness that eliminating and suppressing solutions exist the problem with the impact of vibrations does not abate, just on the contrary. The process of urbanisation proceeds, the number of constructed roads and buildings increases and there are more and more vehicles. Therefore, prevention and proper diagnostics are equally important. The methodology used to determine the influence of vibrations depends on the situation under analysis [Kawecki et al. 2014]. The first method consists in developing a computational model for a building and subjecting it to kinematic excitation. For example, the finite elements methods is used, where both the building and the source of vibrations are to be designed, i.e. there are no buildings or roads within the given area. The second possibility is the situation where the building is contemplated and the source of vibrations is known, for example, the existing road being in operation. In such case the ground vibrations are measured in the future location. Another situation to be considered concerns the building in operation and the contemplated source of vibrations, in which case vibrograms produced under similar measurement circumstances are used. The building being in operation and the known source of vibrations represent the last and most frequent case, which is described in section 3.

1.2. Passive impact of vibrations on people staying in the building

People making use of the building are usually passive recipients of vibrations, having no influence on their source [Kawecki et al. 2014]. The provisions of the Polish law (see the standard [PN-B-02171:1988]) define the permissible values that ensure the so-called vibration comfort. There are two assessment parameters in [PN-B-02171:1988]. The first one is the corrected value of acceleration (velocity) of vibrations within the frequency band of 1-80 Hz. The correction [Kawecki et al. 2014; PN-B-02171:1988] is effected by placing a correction filter in the measurement channel – which results in the corrected root mean square acceleration or velocity value. The human perception threshold of vibration for this parameter has been specified in the standard [PN-B-02171:1988]. The other method relies on the spectrum of the root mean square acceleration or velocity value within the 1/3 octave bands. The procedure used for this testing method is similar to the one applied to determine the influence of vibrations on the building, with the only difference being the human perception threshold, which is lower than the perception threshold for structures [Kawecki et al. 2014]. Another difference is the fact that when the influence on people is evaluated three directions of vibration impact have to be considered: two horizontal (X, Y) and one vertical (Z) directions, whereas in the case of structures only two horizontal (X and Y) directions are analysed.

2. Measurement methodology

The measurement methodology described hereinbelow is used most often, i.e. in the case where the building is in operation and the visual assessment and occupants' perceptions lead to the presumption that the building is subject to traffic impacts. It is necessary to use specialist measuring instruments and appropriately calibrated sensors, measuring the parameters of building vibrations (velocity, acceleration) [see Kawecki 2011; Kawecki and Stypula 2008; PN-B-02170:1985]. Three sensors at a minimum are attached to the wall facing the source of vibrations, at the ground level. Usually two sensors are placed at each of the measuring points – one in the direction perpendicular to the wall and the other in the direction parallel to the wall. During the passage of different types of vehicles time series are recorded. When the database has been collected, the analysis should be conducted in accordance with the standard [PN-B-02170:1985. After the data have been processed, the extreme values should be determined, for example acceleration values recorded at the given measuring points within the 1/3 octave bands, within the range of 0.5-100 Hz [Bendat and Piersol 1971]. The standard [PN-B-02170:1985] contains graphs showing acceleration as a function of frequency, the so-called Scales of Dynamic Influences (SDI) for two cases:

- **SDI I** – scale for delineating the zone of dynamic influences on brick buildings with small (maximum 15 m) footprint perimeters and heights that do not exceed the perimeter value [PN-B-02170:1985],
- **SDI II** – scale for delineating the zone of dynamic influences on brick buildings having up to five storeys, the height of which is below the smallest width doubled [PN-B-02170:1985].

After the analysis the extreme values for 22 centre frequencies are plotted onto the graph showing acceleration as a function of frequency and it is checked which risk zone a given building belongs to:

- **Zone I:** no vibration influence on the building,
- **Zone II:** vibrations perceptible for the building, but harmless to its structure,
- **Zone III:** vibrations may generally impair the load-bearing capacity of the structure,

– **Zone IV:** vibrations significantly affect the structure, posing a threat to people,
– **Zone V:** the load-bearing capacity of the building has been compromised, a failure or disaster is possible.

2.1. Example of the conducted vibration testing

Measurement tests were conducted for a single family building, made of brick, and situated at a distance of 11 m from the edge of the roadway. Vibrations were caused by passing buses, trucks and also passenger cars.

Fig. 1. Example of a building subject to vibration measurement tests (on the left), sensors installed on the wall near the ground level (on the right)
Source: [own elaboration].

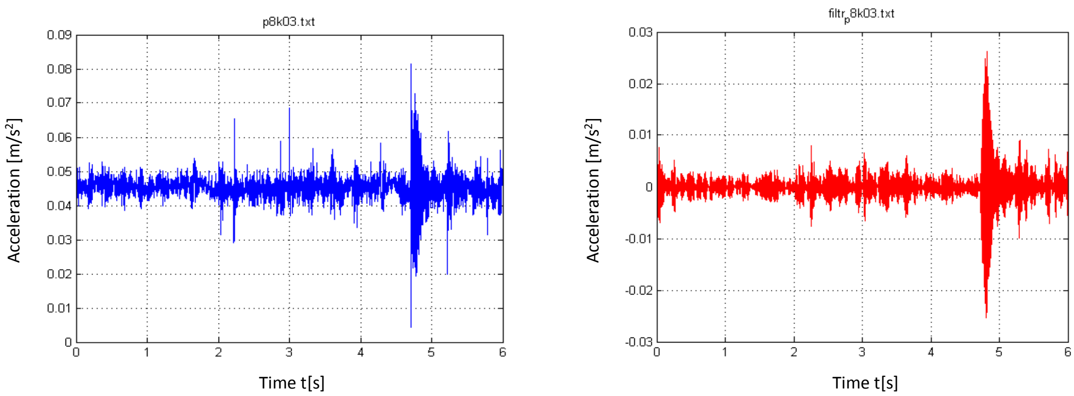

Fig. 2. Examples of acceleration time series before filtration (on the left) and time series after filtration for the centre frequency of 63 Hz (on the right)
Source: [own elaboration].

A set of 12 time series was performed, lasting 6 or 8 seconds. Then, the analysis according to the standard was conducted, following the principles described in [Kawecki and Stypula 2008; PN-B-02170:1985]. Below, the examples of graphs showing the measured time series before and after filtration in the given frequency band are presented.

After conducting the full analysis (within the range of 0.5-100 Hz) a graph was prepared for SDI I, presented in Figure 3. It should be noted that the measured values indicate Zone I, which means that road vehicles exert no influence at all on the examined building. The completion of measurements and detailed analysis is a labour-consuming process and, what is more important, requires the use of professional equipment. Any methods making it possible to determine preliminarily whether or not a given facility is at risk, without taking field measurements, would be welcome. The next section presents the idea of employing Bayesian networks to determine probabilistically the degree of hazard posed by dynamic effects. It is one of the numerous methods of forecasting the influence of vibrations on buildings (see also [Jakubczyk-Galczynska et al. 2015, 2016; Siemaszko and Kemblowski 2016]).

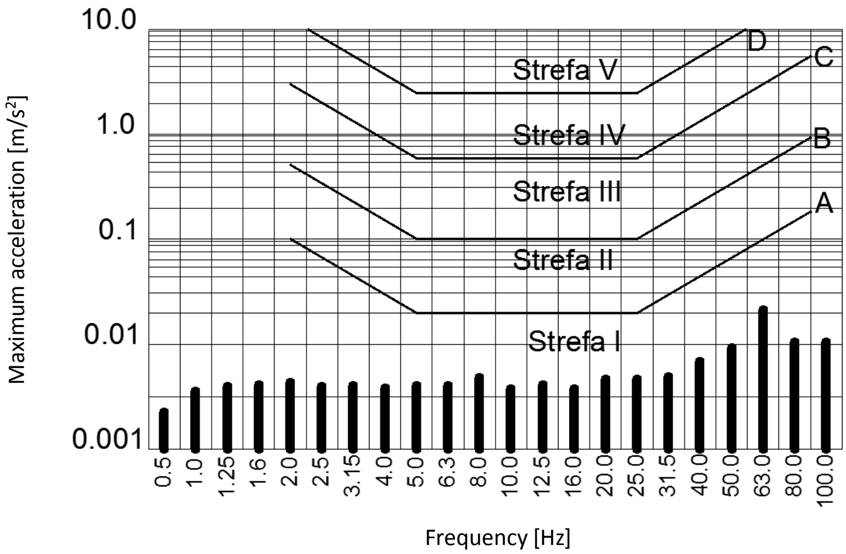

Fig. 3. SDI I with the plotted maximum acceleration values
Source: [own elaboration on the basis of [PN-B-02170:1985]].

3. Operational problems in buildings

3.1. Taking operational decisions

Decisions regarding the operation of building structures are most often taken under conditions of uncertainty, i.e. in situations where the possibilities of occurrence of a specific state are not known or not entirely known. The consequences of taking a given decision depend on some factor which is not known with absolute certainty. Therefore, the possibility of occurrence of respective events should be considered and, then, the probability of their happening should be determined.

The decision-making process is defined as an activity aimed at selecting one from among the available actions *a*1, *a*2, …, *an*, forming the action space *A*, and a decision tree is its graphical representation [Kjaerulff and Madsen 2008]. One of the possible approaches supporting this process is the Bayesian decision theory, which provides a mathematical model making it possible to capture the blurring of notions when data are uncertain [Benjamin and Cornell 1977]. The logical basis for selecting from among the alternative actions of the space *A* is the expected value, which can be defined as the sum of products of the probability value and utility (loss) on the occurrence of a specific event. In the decision-making process the decision-maker is required to determine numerically the selection of his preferences. The transitivity principle is applicable here, according to which in the case where the decision-maker gives priority to consequences *A* over *B* and *B* over *C*, it means that priority is also given to *A* over *C*. The description of selection preferences becomes about the determination of the function of utility *u*, which attributes some numerical values to consequences *A*, *B* and *C*, on the assumption that: $u(A) > u(B) > u(C)$ [Kjaerulff and Madsen 2008].

In recent years Bayesian methods have become the key to evaluating and analysing uncertainty. Numerous publications have shown that Bayesian networks can be used as an effective tool in relation to safety issues [Benjamin and Cornell 1977] and up till now they have been employed in different disciplines, including, among others, technical diagnostics, but also in medical diagnostics. The successful use of Bayesian networks is promising for the construction industry and, therefore, it is clearly necessary to verify the possibilities of applying this methodology for assessing the influence of vibrations on building structures.

3.2. Idea of employing Bayesian networks

Bayesian networks are sometimes referred to as the so-called belief or causal networks. The name of the network comes from the author of the conditional probability theory, Thomas Bayes [Benjamin and Cornell 1977, Kjaerulff and Madsen 2008]. The conditional probability is a fundamental probabilistic tool with numerous applications, used, among others, to build networks [Kjaerulff and Madsen 2008]:

$$P(A \mid B) = \frac{P(A,B)}{P(B)} = \frac{P(B \mid A) \cdot P(A)}{P(B)} \quad (1)$$

where:

$P(A|B)$ – a posteriori (after the experiment) probability of the occurrence of event *A* based on the observation of phenomenon *B*;

$P(B|A)$ – probability of the occurrence of event *B* on the assumption of a specific state of event *A*;

$P(A)$ – a priori (before the experiment) probability reflecting the belief in the occurrence of event *A*;

$P(B)$ – probability defined jointly by the a priori probability of the occurrence of event *A* and the conditional probability:

$$P(B) = \sum_{j=1}^{N} P(B \mid A_j) \cdot P(A_j) \quad (2)$$

where:

j – specific state of event A, where j = 1, 2, 3, …, N;

N – number of adopted states of event A.

On the basis of correlations between variables the Bayesian network makes it possible to calculate the probability of events. In practice, the available and current information is entered into the network, thus updating the distribution of probabilities taking account of subsequent random variables. Algorithms defining the probability are highly complex, however, the updating times are very short.

With respect to their use the Bayesian networks can be divided into two basic groups: belief networks, in which it is possible to build only the model of reality and potential solutions for the interrelations identified in this model, and decision-making networks, combining the issues of probability distribution in the model reflecting the reality with decision-making elements. The belief networks are built on the basis of nature nodes only, whereas the decision-making networks comprise also utility (satisfaction) nodes and decision nodes.

3.3. Idea of employing Bayesian networks to forecast the influence of vibrations

This subsection presents the concept of employing networks to evaluate the influence of traffic vibrations on residential buildings. It should be emphasised that the algorithm model is in its initial stage, still developed to enhance its reliability.

Input variables were adopted on the basis of the conducted field tests and the standard [PN-B-02170:1985]. Table 1 presents the parameters and the methods of determination of input variables.

Table 1. Characteristics of input variables

Variable	Method of determination	Range
Condition of the building	Site investigation – *in situ*	bad, average, good
Condition of the pavement	Site investigation – *in situ*	bad, average, very good
Vehicle type	Field measurement	passenger cars, buses, trucks 10-40 t and above 40 t
Ground absorption	Determination on the basis of *Geographic Information System* [Centralna Baza… n.d.] and [Kawecki et al. 2014]	bad, average, good
Distance between the road edge and the building	Field measurement	2-20 m

Source: [own elaboration].

The output variable is represented by the information whether or not the risk of adverse effects of vibrations on buildings exists. The hazard is determined on the basis of the criteria contained in the standard. The lack of risk indicates zone I of vibration effects, that is the lack of any traffic impacts on buildings. If the algorithm forecasts a potential hazard, it forms a recommendation for conducting in situ measurements, as it may suggest that the building concerned belongs to zone II or above.

The model of a decision-making network for the initial evaluation of hazard posed to a building by traffic vibrations is presented in Figure 4. Owing to such model it is possible to establish with a specified probability whether there is a risk of adverse effects of vibrations on the building.

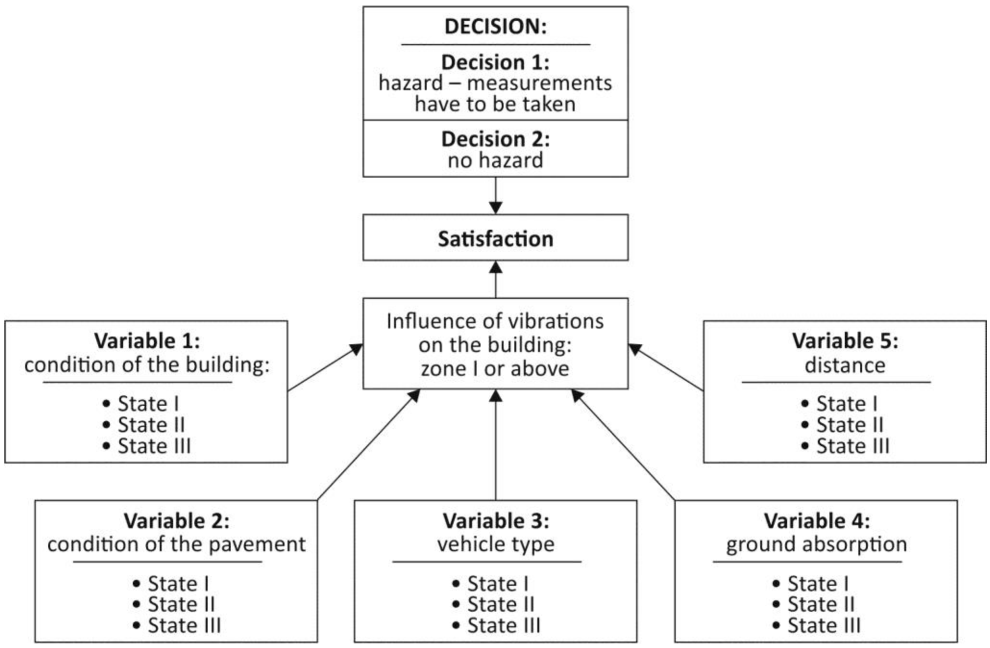

Fig. 4. Bayesian network model for evaluating vibrations
Source: [own elaboration].

3.4. Implementation and operation of the designed network

The input data, collected and classified in the way shown in table 1 should be entered into the model created using a computer program (for example, *Netica)*. After computing the probabilities (projected in the created network) the value of vibration effects is estimated: this is a binary classification with the following responses:

0 – no influence of vibrations on the building – zone I according to the standard [PN-B-02170:1985];

1 – probable influence of vibrations on the building – zone II or above according to the standard [PN-B-02170:1985].

When the value of probability of vibration effects is obtained the decision can be taken whether or not the building is exposed to adverse effects of traffic vibrations, followed by the decision on conducting measurements by an accredited laboratory, or refraining from such measurements, as the estimated probability is low.

Conclusion

Bayesian networks represent one (see also [Jakubczyk-Galczynska et al. 2016]) of the classification tools that can improve significantly the quality of managing the operation of residential buildings. The concept of employing networks to forecast the influence of traffic vibrations on buildings can serve as an example. This paper presents the idea of an algorithm which, upon its completion, may provide the basis for a comprehensive system supporting the decision-making process regarding traffic impacts. The process of taking diagnostic decisions in situ is usually very difficult as well as time-consuming and expensive. Therefore, each tool minimising the consumption of time and costs and, concurrently, serving as a reliable and proven source of information, facilitates the decision-making process. The initial results show that a Bayesian network is a good tool for the preliminary forecasting of vibration effects on buildings and the further activities, aimed at extending the database and improving the quality of the model, are taken to enhance the algorithm and to increase its reliability to the level of at least 80%. In the next stage it is planned to take account of vibration effects as an element of the broader system for assessment and prevention in the operation of building structures. To improve the quality of the process of operating and maintaining residential buildings it is necessary to create a uniform system for managing operational technique, technology and economics.

Acknowledgement

No acknowledgement and potential founding was reported by the authors.

Conflict of interests

The author declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

ORCID

Anna Jakubczyk-Galczynska https://orcid.org/0000-0003-4616-0010

Agata Siemaszko – The author declared that she has no ORCID ID’s

References

Bendat, J.S. and Piersol, A.G. (1971). *Random data: analysis and measurement procedures*. Wiley-Interscience.

Benjamin, J.R. and Cornell, C.A. (1977). *Rachunek prawdopodobienstwa, statystyka matematyczna i teoria decyzji dla inzynierow*. Warszawa: Wydawnictwa Naukowo-Techniczne.

Centralna Baza Danych Geologicznych (CBDG) (n.d.), [online]. Panstwowy Instytut Geologiczny – Panstwowy Instytut Badawczy (website). Available at: http://baza.pgi.gov.pl/ [Accessed: 19 September 2018].

Hunaidi, O. (2000). Traffic vibrations in buildings. *Construction Technology Update*, no. 39, pp. 1-6.

Jakubczyk-Galczynska, A., Kristowski, A. and Jankowski, R. (2015). *Idea zastosowania sztucznej inteligencji w prognozowaniu wplywu drgan komunikacyjnych na odpowiedz dynamiczna budynkow mieszkalnych*. XI Konferencja Nowe Kierunki Rozwoju Mechaniki – Sarbinowo Morskie, 18-20 marca 2015.

Jakubczyk-Galczynska, A., Kristowski, A. and Jankowski, R. (2016). Wykorzystanie sztucznych sieci neuronowych do szacowania wplywu drgan na budynki jednorodzinne. *Materialy Budowlane*, no. 526(6): pp. 116-117.

Kawecki, J. (2011). Dynamic actions on building objects. *Folia Scientiarum Universitatis Technicae Resoviensis*, no. 276, pp. 115-134.

Kawecki, J. (ed.), Dulinska, J., Koziol, K., Stypula, K. and Tatara T. (2014). *Oddzialywania parasejsmiczne przekazywane na obiekty budowlane*. Krakow: Wydawnictwo PK.

Kawecki, J. and Stypula, K. (2008). Bledy w diagnozach dotyczacych oceny wplywow dynamicznych na budynki. *Czasopismo Techniczne*, no. 1-M, pp. 127-136.

Kjaerulff, U.B. and Madsen, A.L. (2008). *Bayesian Networks and Influence Diagrams. A Guide to Construction and Analysis*. Springer Science+Business Media, LLC.

Kuzniar, K. (2002). Estimation of dynamic response of buildings with load bearing walls using response spectra and neural networks. *Journal of Theoretical and Applied Mechanics*, no. 40, pp. 483-495.

Kuzniar, K. and Waszczyszyn, Z. (2007). Neural networks for the simulation and identification of building subjected to paraseismic excitations. *Intelligent Computational Paradigms in Earthquake Engineering*, pp. 393-432.

PN-B-02170:1985. (1985). *Ocena szkodliwosci drgan przekazywanych przez podloze na budynki*. Warszawa: Polski Komitet Normalizacji Miar i Jakosci.

PN-B-02171:1988. (1988). *Ocena wplywu drgan na ludzi w budynkach*. Warszawa: Polski Komitet Normalizacji Miar i Jakosci.

Siemaszko, A. and Kemblowski, M.W. (2016). Ocena efektywnosci monitoringu obiektow inzynierskich za pomoca sieci Bayesa. *Materialy Budowlane*, no. 6(526), pp. 1-2.

Biographical notes

Anna Jakubczyk-Galczynska – M.Sc., Eng., Assistant and Doctoral Student, areas of interest: traffic vibrations, machine learning, management in construction; grants awarded by the University and under the Advanced Phd Project; co-organiser of scien-

tific conferences and the "Girls as Engineers" campaign; member of the Polish Group of Seismic and Paraseismic Engineering; 16 scientific publications.

Agata Siemaszko – M.Sc., Eng., Assistant and Doctoral Student, areas of interest: operation of building structures, diagnostics, management in construction, methods supporting decision-making, expert systems; author of seven scientific publications in the peer-reviewed journals and monographs; co-organiser of scientific conferences and the "Girls as Engineers" campaign; winner of two national contests for the best masters theses.

How to cite this paper

Jakubczyk-Galczynska, A. and Siemaszko, A. (2018). Vibration testing in buildings and safety of their operation. *Scientific Journal of the Military University of Land Forces*, vol. 50, no. 3(189), pp. 144-154, http://dx.doi.org/10.5604/01.3001.0012.6233