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# Consideration of Criteria of Vibration Comfort of People in Diagnosis and Design of Buildings

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***Abstract*—**The increasing influence of traffic on building objects and people residing in them should be taken into account in diagnosis and design. Users of buildings expect that vibrations occurring in their environment, will not only lead to damage to the building or its accelerated wear, but neither would affect the required comfort in rooms designed to accommodate people. This article describes the methods and principles useful in designing and building diagnostics located near transportation routes, with particular emphasis on the impact of traffic vibration on people in buildings. It also describes the procedures used in obtaining information about the parameters of vibrations in different cases of diagnostics and design. A universal algorithm of procedure in diagnostics and design of buildings taking into account assurance of human vibration comfort of people residing in the these buildings was presented.

***Keywords*—**diagnostics, influence of public transport, influence of vibrations on humans, transport vibrations

## I. INTRODUCTION

INCREASINGLY, in urban and peri-urban spaces experts and designers of buildings should take into account in their analyses impact of vibration on buildings and people living in them. Users of buildings expect that vibrations occurring in their environment, will not only lead to damage to the building nor its accelerated wear, but would neither affect the required comfort in rooms designed for accommodation of people. In more densely populated urban areas, the number of traffic vibration sources is growing. Having more and better tools for modelling and analysis of the structure and effective means for vibration insulation the requirements specified by the users of buildings can be met. So the increasing interest of civil engineers in problems of impact of vibration on buildings and people residing in them (Fig. 1) is understandable.

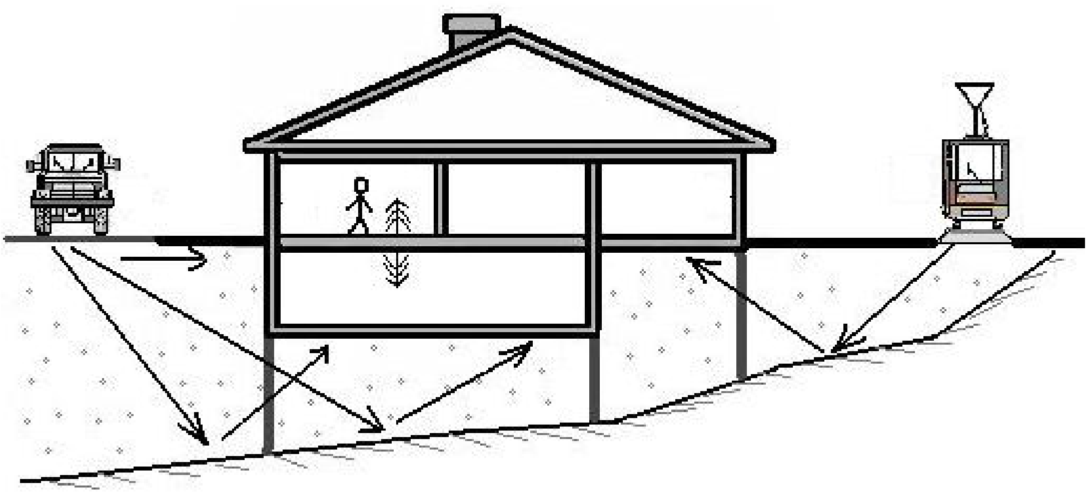

Fig. 1 Sketch illustrating transmission of traffic vibrations on buildings and people in them

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This article aims at provideing methods and criteria useful in design and diagnosis of buildings including the impact of vibration on people in buildings located in the vicinity of sources of transport vibration. Using the given procedures a level of vibration in buildings that will not violate the necessary comfort in rooms designed to accommodate people should be assured.

## II. Diagnostic and Design Situations

In diagnostic evaluation and design of structures including impact of vibration on humans five situations can be distinguished depending on the state in which the source of vibration and the object receiving vibration during the diagnosis and design is. Classification is given in Table I.

TABLE I
DIAGNOSTIC AND DESIGN SITUATIONS

| No. | Name of situation | Source of vibration | Object receiving vibration |
|---|---|---|---|
| 1 | diagnosis | active | executed |
| 2 | diagnosis with forecast | designed | executed |
| 3 | designing | active | designed |
| 4 | design with forecast | designed | designed |
| 5 | diagnosis with forecast (a posteriori) | previously occurred (it is not reaction possible) | realized (now in position of damage) |

Dynamic diagnosis usually refers to the first case. Then vibrations are transferred from an existing source of vibrations to the completed building object. the results of direct measurement of vibration are used in diagnostic evaluation. If the assessment concerns the impact of vibration on humans, the measurement is made at the receiving end of vibration by man (on floors of particular floors). Thus, obtained results, after undergoing procedure of analysis are compared with the accepted criterion for comfort. Situations: the second and fifth also refer to diagnosis, but the assessment of the dynamic influence is done basing on the prediction of vibration. Projected values are determined analytically, taking into account the measurement data collected in a database of such data. The size of the measurement database and accuracy of description of the input parameters affects accuracy of diagnosis in these cases.

Situations: the third and fourth are included in the task of designing. The values of predicted vibration parameters are determined like in the second and the fifth situation. There is no possibility of experimental verification of the adopted calculation model of the building because the object is in design phase.

The results of the analysis in all these situations become the basis for assessing the impact of vibrations on the receiver. As described here, the receivers of vibrations are people living in buildings. If the analysis proves that the conditions of the necessary comfort of people living in buildings have been violated , then appropriate technical measures should be used to reduce vibration levels received by people. Technical measures can be applied to the source of vibration, through their propagation or to the object receiving vibrations. Further analysis should allow to select the most advantageous (in terms of practical implementation, cost, availability of materials, etc.) method of reducing vibration.

Analysis of the impact of vibration relates to facilities located mostly in the so-called zone of dynamic influence. These zones have various ranges depending on the type of vibration sources, their propagation path and the dynamic characteristics of the building which receives vibrations. Table II summarizes the zones of influence, for example, ranges of vibrations generated by different sources.

TABLE II
ZONE OF INFLUENCE OF VARIOUS SOURCES OF VIBRATIONS (ACCORDING TO [13])

| Source of vibration | Range of the influence zone |
|---|---|
| Railway line | 25-50 m |
| Tram line, wheel road | 15-25 m |
| Line of a shallow underground | 40 m |
| Driving of foundation piles | 40-60 m |
| Soil compaction by vibratory roller | 20-60 m |
| Driving of sheet piling with vibratory hammer | 30 m |
| Driving of sheet piling with shock hammer | 20 m |

On the basis of the summary it can be seen that at typical conditions road and rail vibrations are smaller than the range of influence of vibration caused by work of vibratory rollers. This shows the need of including in analysis of dynamic action of vibration sources, not only during the operation, but also during road construction.

It should also be noted that the information contained in Table II, concerning indicative ranges of vibration impact zone relate to their impact on the building structure. They can not be directly related to the extent of the effects of vibration on people in buildings.

## III. Procedures of Obtaining Information on the Parameters of Vibrations

In the case of an existing source of vibration necessary information on the parameters characterizing oscillations can be obtained from measurements. Measurements apply to selected points on the building. If the assessment relates to the impact of vibration on people in the building, then the measurement points are located in areas of vibration reception by the people (on the ceiling). During such measurements it is worth to expand the program of research in order to obtain additional information such as on influence of the propagation path of vibration on parameters describing them and on the degree of vibration reduction at transition from the ground on the foundation of the building. The results of such measurements increase the base of measurement data, which is used in studies related to the designed source of vibration (situations 2 and 4 in Table I).

In the following the situations described in Table I are considered in terms of acquiring information on vibration parameters.

### *A. Vibration Source is Active*

In the case of a completed building the kinematic parameters are obtained by measuring vibrations on the foundation or basement wall of a building. If the assessment concerns the impact of vibration on humans, the measuring point should be located at the place of reception of vibrations by people (mostly on the floors of the building, measured in three directions: x, y, z).

In the case of designed building the assessment is carried out considering the calculation model of the building (mostly FEM). Such a model allows to determine additional forces that burden the structure as a result of the measured vibration excitation. Basing on the analysis of the model of the building the response is obtained at any point, including the place of receipt of vibration by human. The requirements to provide comfort to people residing in the building are checked using appropriate criteria of assessment. In the case of the non-fulfillment of this requirement a change in the building structure is introduced and calculations are repeated until the target is met.

### *B. Vibration Source is Designed*

In determining the reaction of the building to predicted dynamic action the collection of information contained in the database is used and the most likely description of the vibration excitation of the building is set. Then the calculation model of the designed or completed building is subjected to forecasted kinematic excitation. If the building is completed, then after the model verification and after ensuring compliance with the real object the forecasted excitation is applied to the model and its dynamic response in the places of receiving vibration by people is determined. Parameters designated in this way are used in assessing of the impact on people in the building.

If the building is designed, then after the model is made the forecasted excitation is attached to the model and the vibrations are determined in characteristic reception areas of vibration by human. The designated parameters are used in the assessment. If the relevant requirements are not satisfied so as in the case when the vibration source is active and the building designed - necessary changes in the structure are introduced and calculation is repeated until the target is achieved i.e. providing people with the required vibration comfort.

## IV. THE CRITERIA USED IN ASSESSING IMPACT OF VIBRATION ON PEOPLE IN BUILDINGS

In many publications and standards criteria of evaluation of vibration impact on people in buildings are given. One may recall here the provisions contained in [1, 3, 4, 5, 6, 7] and in the standards: Polish [2], the international ISO [8] British [9] and German [10].

Assessment of vibration impact on humans is conducted on the basis of parameters specified in the standards [2, 8, 9, 10], depending on the method used for assessment. Mostly used is the method that uses the spectrum effective value (RMS) acceleration (or velocity) of vibration in the 1/3 octave bands (see [1, 8]) or a method based on the so-called. VDV vibration dose (cf. [8, 9]).

Parameter values obtained from measurements are compared with corresponding values of providing the comfort. While determining the value of providing more comfort vibration (upper limit of the vibration level), influence of many factors is taken into account, including the following:

- purpose of the room in the building,
- time of occurrence of vibration,
- nature of vibrations and their repeatability,

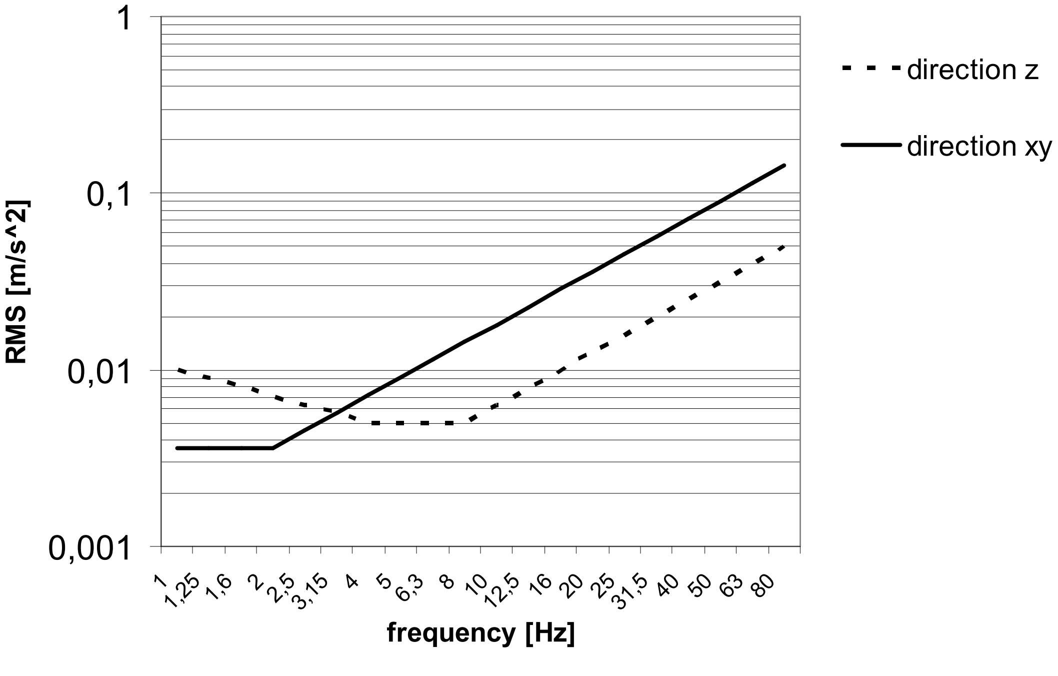


Fig. 2 Basic lines corresponding to the sensation threshold of vibration

- direction of vibration and position of the human body in relation to this direction of vibration,
- vibration frequency.

The vibration dose value of the coefficient VDV also takes into account the total duration of human exposure to vibration. Room designation, time of occurrence of vibrations and their repetition influences the value of "n" factor, which is given in the tables contained in the standards [2, 8]. Effect of vibration direction of reception by the body and frequency of vibration is included in lines characterizing the so-called sensation threshold of vibration. Fig. 2 summarizes the sensation threshold lines of vibrations received by in the direction (feet-head) and in the xy directions (back-chest, side-side).

In the standard [2] in assessing the impact of vibration on humans a simplified criterion is allowed, in which there is a corrected value of acceleration (or velocity) of vibration in the whole frequency band (from 1 to 80Hz). In such a method of assessing the value of the corrected vibration acceleration ($a_k$) corresponding to the analyzed direction of reception (z, xy) should satisfy the condition:

$$a_k \leq a_{kl} \cdot n \qquad (1)$$

where: $a_{kl}$ - corrected acceleration value corresponding to the sensation threshold of vibration transmitted to humans in the direction z or xy, adopted from the standards [2,8]

n - value of the coefficient which takes into account the impact of destination of the room, time of occurrence of vibration, nature of vibrations and their repeatability.

Basing on the evaluation using the corrected value of information is obtained only whether there is a violation of requirements referring provision of the necessary comfort to people residing in the building. Fuller information on the impact of vibration on people is obtained on the basis of the RMS acceleration (or velocity) of vibration in 1/3 octave band. The RMS value of acceleration $a(f_i)$ in each 1/3 octave band with center frequency $f_i$ corresponding to the analyzed direction of vibration should fulfill the condition:

$$a(f_i) \leq a_1(f_i) \cdot n \qquad (2)$$

where: $a_1(f_i)$- RMS value of vibration acceleration corresponding to the sensation threshold of vibration according to the standard [2, 8],

n - value of the coefficient which takes into account the impact of the room destination, time of occurrence of vibration, the nature of vibrations and their repeatability.

Basing on the assessment carried out by use of the effective value (RMS) acceleration (or velocity) of vibration in 1/3 octave bands information is obtained whether and in what frequency bands infringement of the conditions of necessary comfort occurred. An example of such an analysis is given by [11] in Fig. 3.In the assessment of the impact of vibration on people in the building also apply the method in which the evaluation parameter the so-called vibration dose value (VDV) is applied. The value of this parameter is determined by the formula:

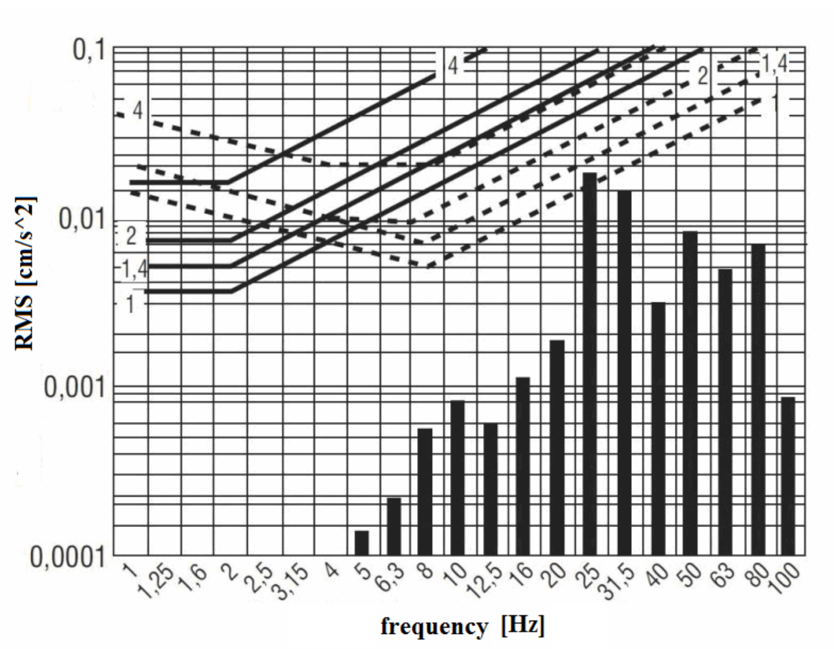


Fig. 3 Example of analysis of the effects of vibration on people in building [11]

$$VDV = \left( \int_0^T a^4(t)dt \right)^{0.25} \quad (3)$$

where: a(t) - the value of the acceleration as a function of time, T - total duration of vibration.

The determined value of the vibration dose (VDV) is compared with the values given in standards [8,9]. In the appropriate table the three levels of sensation threshold of vibration are described. Level one (low probability of complaints from users of premises) is comparable with the sensation threshold of vibration determined in standards [2,8]. Highest level (greater probability of complaints from residents) is compared with the upper vibration comfort limit.

## V. Diagnostic Procedures Relating to People in Completed Buildings

For people living in completed buildings there could be two cases: the source of vibration is operated (then diagnosis of the impact of vibration is done) and the source of vibration is designed (then diagnosis is done with the forecast.)

Dynamic diagnosis of impact assessment of vibration on people living in the completed buildings and passively receiving vibrations generated by the operated source of vibration includes the following steps:

- collection of data on allocation of the room in which people reside,
- collection of data on sources of vibration, whose effects on humans can be significant and the way of propagation of vibrations from the source to the place of their reception by the man
- acceptance of the assessment criterion,
- determination of the values of the parameters characterizing the vibrations at their reception by man based on measurements,
- assessment of the impact of vibration on humans according to criterion
- proposition of technical measures leading to reduction of vibrations in the case of evidence of infringement of the required vibration comfort.

The above given diagnostic procedure is modified if the source of vibration is in a design phase. Then an important step in diagnosis is determination of projected parameters of kinematic excitation and adoption of a computational model of the completed building. Developing a computational model of the building is mostly realized using the FEM. It must be stressed however that there is a need to redefine the model by measuring the vibration of the building caused by another, applicable vibration source. Such a model can be verified using the measurements of the so-called dynamic backgrounds [cf.12, 13].

## VI. Diagnostic Procedures Relating to People Who Will Stay in the Designed Buildings

In the case of people who will stay in the designed buildings two situations can occur: the source of vibration is already in operation (then the building is designed knowing the parameters characterizing the kinematic excitation) and the source of vibration is also designed (then the building is designed to the forecasted parameters of vibration).

In both these cases, the kinematic excitation parameters of the building are determined using the data contained in the database of measuring. In the first case more information is needed about the degree of vibration reduction when transferring them from the ground (measured) to the foundation of the designed building, while in the second case from the database of measurements full information is obtained about the parameters of the forecasted vibration excitation.

The building should be designed so that its vibrations do not infringe the necessary conditions for a particular comfort for people staying in the rooms.

Key elements of the building design process, taking into account the impact of vibrations on people who will reside in it are given below.

If the source of vibration exists, then:

- ground vibrations at the future location of the building are being measured ,
- kinematic excitation parameters of the building (vibrogram) are determined using information on the results of measurements contained in the database corresponding to similar situations measurement results of reduction of vibrations at the crossroads: the ground - the foundation of the building,
- after shaping a computational model of the building the motion in the place of vibration reception by man is determined,
- with regard to analytically determined vibrograms appropriate criteria for assessment of the effects of vibration on humans are applied,
- if relevant requirements are not satisfied, changes are made in the structure in such away as to obtain the condition for providing people with vibration comfort required.

If the source of vibration is designed, then:

- basing on a collection of information contained in the database of measurements the most likely description of the vibration excitation of the building is determined and this description is applied to a model of the proposed building,
- vibrations of the building in the place of receipt by human are determined,
- determined parameters are used in assessing the impact of vibrations on human according to the adopted criterion (corrected value, RMS value in 1/3 octave band, value of VDV)

- if the relevant requirements are not satisfied, changes are made in the building structure and the calculation is repeated until the goal of meeting the requirements for the designed building to the effect of vibration on people is reached.

## VII. MAPS OF FORECASTED DYNAMIC IMPACTS

In some practical situations it is necessary to identify the impact of vibrations generated by a new source of vibration caused by changes in the conditions of an existing source of vibration. This may for example relate to changes in traffic conditions along an already existing, but modernized road, railway or subway. The global assessment of the impact of new sources of vibration on the existing buildings and people in the buildings may be associated with development of a map of the forecasted dynamic impact.

Carrying out immediate studies in selected characteristic sections during the passage of the existing vibration source and having the data in the measurement database map of forecasted dynamic influence resulting from changes of the characteristics of the previous vibration source could be developed. An example of such a map is shown in [1].

Such maps can be used in designing of new buildings located in the vicinity of the designed traffic sources of vibration with regard to the planned new traffic-road conditions. After introduction of a new source of vibration, it is appropriate to carry out immediate dynamic studies in selected locations in order to verify the forecasted values included on a map of dynamic influences.

In the procedure of this kind of project there are two clear stages of measurement, in between there is the stage of computing. These stages can be described by the following tasks:

Stage I (Measurement of dynamic backgrounds) includes such tasks as:

- recognition of the area covered by influence of the designed source of vibration,
- selecting buildings, which due to their location relative to the source of vibration, condition and destiny should be covered by individual dynamic analysis,
- performing measurements so-called dynamic backgrounds, that is performing of measurements on selected objects of currently occurring vibrations generated by vibration sources or on a specially applied vibration source model.

Stage II (calculation of the forecasted situation) includes such tasks as:

- verification of the adopted computational models of the building based on measurements taken in stage I,
- selection from the measurement database of vibrograms best suited to operation of the designed source of vibration,
- application use of forecasted vibrograms as kinematic excitation of computational models,
- assessment of the forecasted impact of vibration on people residing in the designed building,
- in the case of exceeding the required level of comfort (or safer: sensation threshold of vibration) introduction of possible changes in building structure to reduce the dynamic influence or in calculations taking into account application of other technical measures to reduce vibration.

Stage III (measurement verification of compliance of the executed building with the criteria for assessment of impact of vibration on people residing in it) includes tasks such as:

- performance of measurements on an object previously covered by analysis after modernization of the source of vibration,
- performance of assessment of influence of registered vibration on people,
- in the case of infringement of assessment criteria, application of additional technical measures to reduce vibration.

Additionally, in all these stages influence of vibrations impact generated during the building (or rebuilding) of the designed source of vibration should also be considered. In particular, it is necessary to take into account in the analyses work of vibratory rollers, vibration hammers and other devices.

## VIII. CONCLUSION

The article presents the diagnostic and design situations that may occur when assessing the impact of vibration on people in buildings. It describes in detail the procedures which should be used in such evaluations. They depend on what the kind of situation which is considered (diagnosis, design).

Most frequently a case of diagnosis occurs of a situation in which there is a source of vibration and an object which receives vibration. Then the diagnosis is performed by measuring the vibrations at their reception by man and the result of this measurement is compared with the criterion of providing the necessary comfort to people. In the case of the task of designing on forecasted vibration (designed vibration source and the designed building which is in the zone of influence of this source of vibration) is need to estimate possible excitation of the building based on similar diagnostic situations. Information contained in the measurement database data are helpful in it . If the building is in design a calculation model (FEM) should be made and - if possible – its verification in the field of vibrations and dynamic backgrounds should be carried out.

The paper summarizes the procedures, which can be useful for the diagnostician or designer, if it is necessary to include in his task traffic vibration impact on people living in the building.

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