



INVESTIGATION OF TRAFFIC-INDUCED VIBRATION IN VILNIUS ARCH-CATHEDRAL BELFRY

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Abstract. The influence of city traffic-induced vibration on Vilnius Arch-Cathedral Belfry is investigated. Two sources of dynamic excitation are studied. Conventional city traffic is considered to be a natural source of excitation while excitation imposed artificially by moving a heavily loaded truck is considered to be the source of increased risk excitation. The influence of induced vibrations is recorded by accelerometers located in various positions of the Belfry's structures and shown by accelerograms. Dynamic effects are evaluated by considering acceleration magnitudes and response spectra. A comparative analysis of both effects is presented and conclusions and recommendations are provided.

Keywords: dynamic experiment, dynamic loading, traffic, accelerations, response spectra, historical heritage.

1. Introduction

The Old Town of Vilnius, which is one of the largest in Eastern Europe, has many buildings of cultural and historical value, making Lithuanian historical heritage, e. g. Arch-Cathedral Basilica, Arch-Cathedral Belfry, St. Ann's Church, the Town Hall, Tymo Quarter, Gediminas Tower etc. As is a common practice in the world, these buildings making historical, architectural and the cultural heritage, are protected by the state. Various laws and regulations have been issued to control traffic, the reconstruction of old and new buildings as well as the development of infrastructure in the Old Town of Vilnius.

The preservation of buildings having a historical value is a complicated problem associated with great expenses. It is important to observe the first signs of destruction in time, to identify their causes and to take effective measures to prevent it.

All factors causing building destruction may be divided into three groups:

- 1) natural aging of buildings in time and under the exposure to the weather;
- 2) the settlement of building foundations caused by changed hydrological conditions and soil characteristics. The settlement of building foundations causes the large deformations of building structures resulting in building destruction: cracks in the walls (especially stone walls) appear and inadmissible vertical deflections are developed.

- 3) Vibrations and impact loads acting on building constructions. These effects are caused by natural phenomena (e. g. earthquakes, wind etc.), (Witzany and Cejka 2007; Witzany and Zigler 2007) and by human activities, e. g. explosions, traffic etc. (Vaidogas 2006a and 2006b; Bogdevičius and Vladimirov 2006).

Apart from a few cases, these causes have not been thoroughly analysed in Lithuania (Kamaitis and Pelikša 1975; Kliukas *et al.* 2008).

In this paper, the behaviour of Vilnius Arch-Cathedral Belfry subjected to external dynamic loading induced by city traffic is analysed.

The rapid growth of traffic intensity in the last decade has caused the increase in dynamic load which is not completely controlled, and therefore its effect on the historical buildings of Vilnius Old Town is unpredictable.

A realistic dynamic experiment was conducted to predict the dynamic behaviour of the structure considered. A dynamic action was evaluated by recording the acceleration history of Belfry structures.

2. Traffic-Induced Vibrations

The investigations of traffic-induced vibration of the structures of the old masonry buildings made in Italy, France and Poland show that recently, the level of this type of vibration has considerably increased (Watts 1990; Atkinson *et al.* 1998; Crispino and D'Apuzzo 2001).

Traffic-induced vibration does not represent, in general, an immediate hazard to buildings, but in time it can worsen the state of a building or even lead to its failure. This can particularly be applied to the old masonry buildings having some specific defects (e. g. cracks, vertical deflections, foundation settlements etc.).

The vibrations of small amplitude characterised by a high number of cycles may cause the reduction of masonry strength due to the deterioration of mortar and its detachment from the bricks (Watts 1990; Whiffin and Leonard 1971; Augenti and Clemente 1995). The Heritage buildings are usually built of wood and stone, and therefore are particularly vulnerable to these effects.

Within the historical city centres (including Vilnius Old Town), it is possible to identify a number of factors increasing transport-induced vibrations (Crispino and D'Apuzzo 2001):

- The streets of historical centres are usually paved with surface-tooled stone (to preserve authenticity and the aesthetic view). However, such road surfacing is easily deformed and is more rough compared to the other types of surfacing;
- Municipalities make efforts to restrict the traffic of personal cars in the Old Town seeking to reduce air pollution. However, public transport is getting more intense while vehicles are becoming heavier;
- Heritage buildings or, more exactly, the buildings protected by laws on heritage preservation require particular attention while considering and evaluating the sources of actions that cause additional stresses in the structures and assessing potential damage.

There are three major causes for concern about building vibration because:

- 1) vibration causes defects in building constructions (Hao *et al.* 2001);
- 2) occupants of the building feel disturbed and uncomfortable (ISO 2631:1978);
- 3) it produces a harmful effect on the normal operation of sensitive equipment (Jian 1984).

In spite of the importance of the latter issue, the information on traffic-induced vibration and its effects on heritage buildings remain scarce.

The standards of many countries define ground vibration levels for buildings (e. g. DIN 4150 1984; BS 6472-1992; SN 640312 1978, PN-85/B-02170, Public Law 95-87 1977). Some codes (DIN 4150 1984; Public Law 95-87 1977) define the allowable vibration level in terms of peak particle velocity (PPV) and the corresponding principle vibration frequencies while in the Polish Standard (PN-85/B-02170) admissible vibration is defined in terms of the admissible acceleration of separate construction particles.

If acceleration caused by a vehicle or other object is smaller than 0.1 m/s^2 , it is not dangerous for buildings. When acceleration reaches $0.1\text{--}1.0 \text{ m/s}^2$, micro cracking of building constructions may occur. When acceleration exceeds 1 m/s^2 macro cracks are formed in the constructions implying that they are being destroyed.

In Lithuania, no codes defining the admissible vibration level of buildings can be found. Therefore, the experiences of the neighbouring countries (e. g. Poland) may be used in assessing the vibration of Lithuanian historical buildings.

In general, the problems of historical heritage protection in Lithuania are similar to those found in other European countries because:

- The number of cars is continually growing in Lithuania. Thus, it has increased sevenfold – from 69 cars per one thousand inhabitants in 1980 up to 500 cars in 2007. This trend towards a rapid growth of the number of vehicles in Lithuania in the last decades is similar to that noticed in Western countries (Niewczas *et al.* 2008; Jakimavičius and Burinskienė 2007; Burinskienė *et al.* 2006; Burinskienė and Munch 2003). Based on experimental and statistical forecasts, the level of motorization in 2015 in Vilnius will reach about 600 automobiles per one thousand inhabitants.
- Similar to the most Western European Old Towns, the road surface in Vilnius historical centre is made of surface-tooled stone that increases the level of vibration;
- The Old Town of Vilnius is situated in the area of the confluence of two rivers – Neris and Vilnelė where the soil is weak and highly deformable. This causes the deformation of the base of a road and the occurrence of surface irregularities.
- Traffic is limited in many areas of the Old Town. The routes to public transport such as heavy buses are usually left.
- Many buildings in the Old Town are being constructed or reconstructed and this causes significant shock vibration of the nearby buildings.

It could be stated, however, that the direct measurement methods of transport traffic-induced dynamic loading are still missing.

3. The Materials and Structural Scheme of the Belfry

The wall structure of the Belfry consists of two main parts which differ in geometry and stiffness (Fig. 1 a, b).

The lower part dates back to the 14-th century as a part of fortifications of the Lower Castle. It is constructed of stone masonry, has the annular cross-section and contains the first four floors.

The upper part, containing the remaining three floors, was built several ages later. It has the octagonal cross-section and is made of brick masonry. The wall of the upper part of the building is weakened by a number of openings for windows. Here, the contribution of the openings makes up to 42% through the cross section area and about 20% through the volume of the upper part.

In 1936, the top of the lower part of the structure was covered by a monolithic joist ceiling constructed as a stiffened reinforced concrete slab.

The roof of the Belfry is a light-weight timber dome structure covered by a thin-plate copper shell.

The total weight of the Belfry is about 4 500 tons.

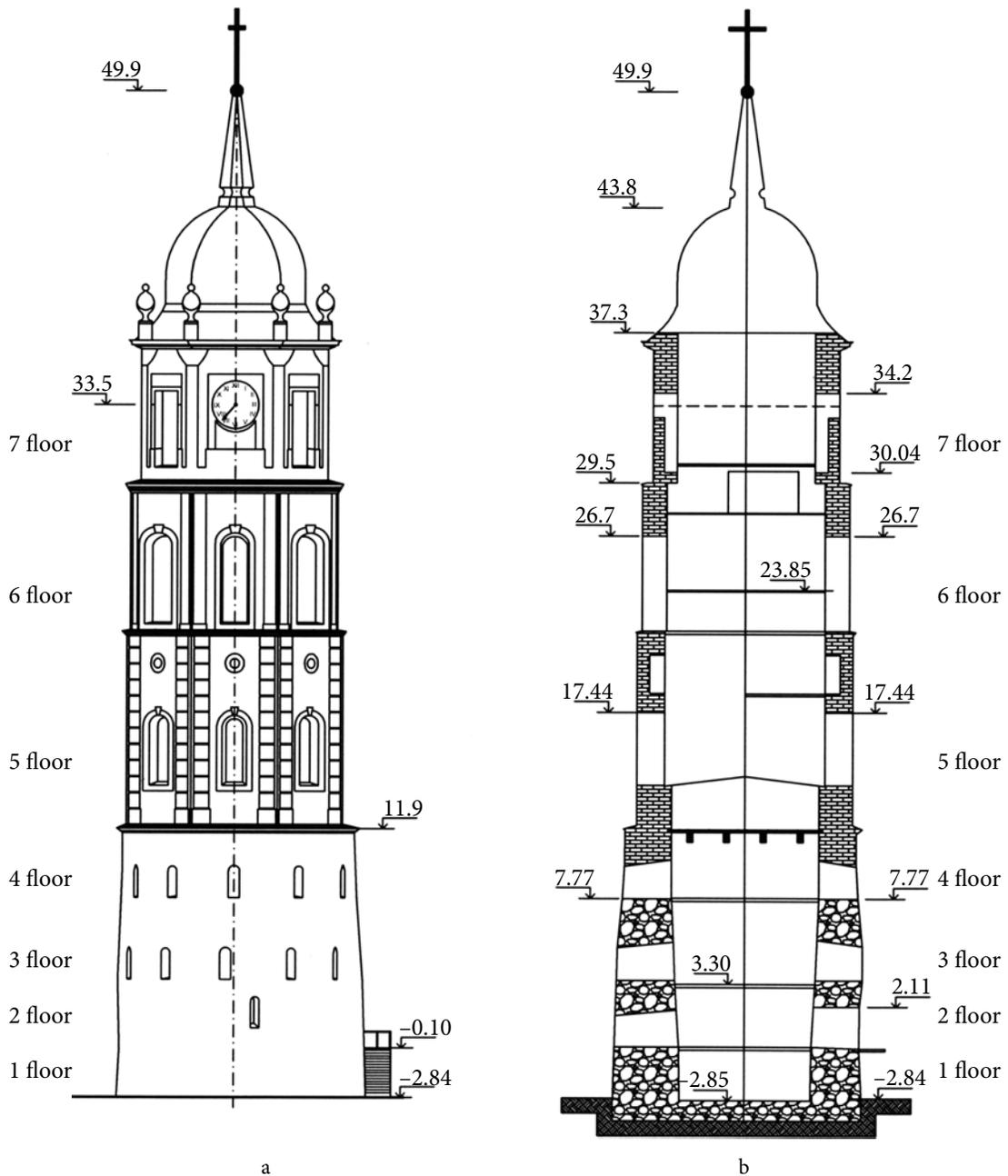


Fig. 1. The Belfry's geometry: a – a general view; b – vertical cross section

4. Investigation of Vibrations

4.1. General comments

This paper focuses on investigation of dynamic external loading on the Belfry structures caused by city traffic.

Two types of external excitation were observed. The first one may be characterized as conventional city traffic-induced background.

In conducting dynamic tests, traffic in Sventaragio and Vrublevskio streets near the Belfry was neither stopped not limited. The conventional city traffic intensity of that time of the day causing the usual vibration level was maintained in these streets over the whole period of testing (i. e. some cars, few trucks and public buses could be observed).

The admissible speed of vehicles in the above mentioned streets is 30 km/h while the traffic of heavy trucks is generally forbidden. However, this does not apply to a few trucks running to the places of their destination in this district (mostly construction sites) found around the Arch-Cathedral Square.

It should be noted that, in 2003, the Gediminas avenue, the neighbouring Vrublevskio and a part of Sventaragio streets were thoroughly reconstructed with no irregularities (pot-holes, steep climbs etc.) causing dynamic loading on the nearby buildings including the Belfry left. However, in time, the situation may change for the worse.

For various reasons, even because of the formation of short – or long – term irregularities on the newly re-

constructed roads heavy vehicles (loaded trucks, overcrowded buses etc.) can considerably increase the dynamic loading of the buildings in the area.

Therefore, the second type of dynamic loading may be considered to be dynamic impact loading artificially induced during the experiment.

During the dynamic experiment, a heavily loaded truck (about 19 tons) was moving along Sventaragio Street in the flow of city traffic (Fig. 2).

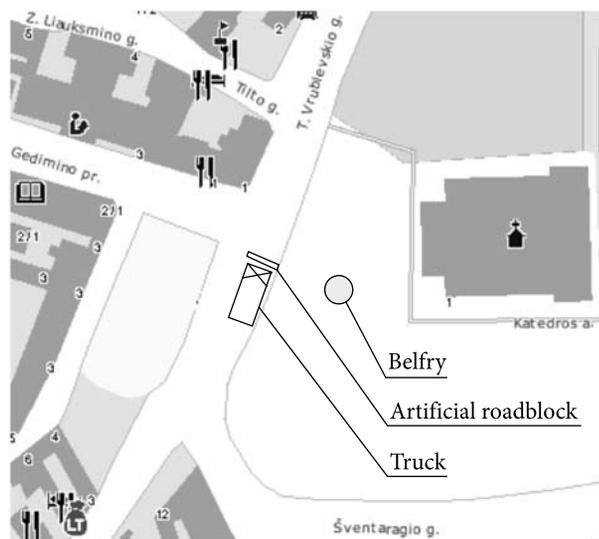


Fig. 2. The scheme of heavily loaded truck movement

In order to appropriately simulate a harmful effect produced by a heavily loaded vehicle running into an imaginary pit-hole or running over an imaginary barrier, an artificial roadblock imitating a localized road surface irregularity was set up on the roadway of Sventaragio Street. The height of the barrier was $h = 10.0$ cm (Fig. 3).



Fig. 3. Simulation of the dynamic impact loading caused by a heavily loaded truck

4.2. Measurement Instrumentation

During dynamic measurements, a mobile set of oscillation measuring devices was used to register vertical and

horizontal oscillations caused by the dynamic action of traffic. The equipment consisted of:

- portable multifunctional analysis system 'PULSE-3560C' (12 channels) and software 7700&7705. Producer *Bruel & Kjaer*, (Denmark);
- 12 one-directional sensors (accelerometers) – type 7752. Producer *Endevco* (USA);
- standard portable personal computer *Hewlett Packard*.

The first layout of accelerometers

Number of accelerometer	Direction of measurement	Altitude [m]	Location of accelerometers
I-1	H, R	21.71	In the window niche (6 th floor)
I-2	H, R	21.71	In the window niche (6 th floor)
I-3	H, R	21.71	In the window niche (6 th floor)
I-4	H, R	21.71	In the window niche (6 th floor)
I-5	H, R	21.71	In the window niche (6 th floor)
I-6	H, R	21.71	In the window niche (6 th floor)
I-7	H, R	21.71	In the window niche (6 th floor)
I-8	H, R	21.71	In the window niche (6 th floor)
I-9	V	7.80	In the window niche (4 th floor)
I-10	V	7.80	In the window niche (4 th floor)
I-11	V	7.80	In the window niche (4 th floor)
I-12	V	7.80	In the window niche (4 th floor)

One-directional vibrosensors were rigidly fixed to the structural elements of the Belfry according to the purposeful layout schemes (Fig. 4).

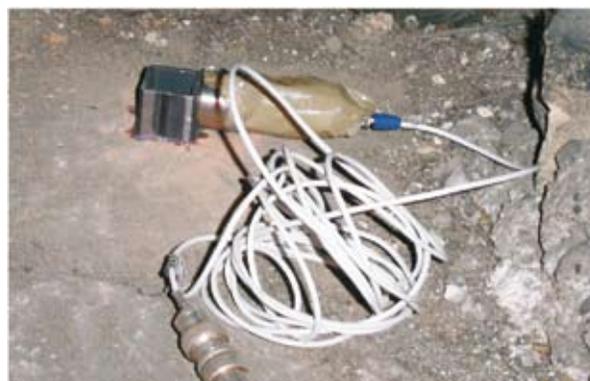


Fig 4. Accelerometer in the working position

The dynamic experiment uses the analytical system 'Pulse-3560C' and three different layout schemes of sensors in typical measurement directions as well as the arrangement of sensors along the vertical axis of the Belfry (from -2.70 m up to 32.9 m).

The basic data on the first layout of the sensors is given in Table, where:

- 1) Accelerometers are placed at the floor level;
- 2) Altitudes [m] are measured at the 2nd floor level.

3) V means vertical, H – horizontal, R – radial.

The signal-registering step of each measurement lasts 7.8125×10^{-3} s while the measurement time-span ranges from 5.119×10^2 to 6.40×10^2 s.

With the aim of eliminating the effect of random disturbances (noise etc.), the recorded signals of vibro-sensors were filtered up to 0.3 Hz and over 60 Hz (the band width was 0.3–60 Hz).

4.3. Measurement Results

The effect of traffic-induced vibrations is recorded in terms of accelerations values.

The obtained results were carefully analysed and the diagrams of acceleration time history were drawn using a commercial program package DynaTool (version 4.1.1). This program provides a collection of tools used by the engineers and scientists involved in seismic analysis.

In the present investigation, the accelerograms of each measurement were attached to each point considered. They provide information about the dynamic effect produced by the action of traffic in various modes and its distribution in the Belfry's structure.

The average values of only one measurement parameter – acceleration allowing us to determine the harmful effect of the particular modes of traffic on the Belfry's structure are presented in the article. The comparative

analysis of the effects produced by transport operating in various modes was performed in the present investigation based on the indication of oscillations in horizontal (at various levels) and vertical directions respectively.

In Figs. 5 and 6, accelerations time histories for 3rd (in horizontal direction, at the level of 21.7 m) and 9th (in vertical direction, at the level of 7.8 m) sensors are presented on the same scale according to the two above-mentioned traffic stages respectively.

Fig. 5a presents the histogram of accelerations in the horizontal direction of the Belfry (at the level of 21.7 m) caused by conventional city traffic. It reflects the background dynamic effect (the usual vibration level) on the building structures. In this case, the accelerations values do not exceed 0.00765 m/s^2 .

While Fig. 5b presents the histogram of accelerations in the same direction at the same level, it is caused by the heavily loaded truck running seven times over a localized artificial road surface irregularity. In this case, the corresponding seven peaks of accelerations are observed. It shows that the effect of heavily loaded trucks on the accelerations values at the level of 21.7 m is by about 6.5 times higher compared to usual vibration level and reaches 0.0498 m/s^2 .

Fig. 6a presents the histogram of accelerations in the vertical direction of the Belfry (at the level of 7.8 m)

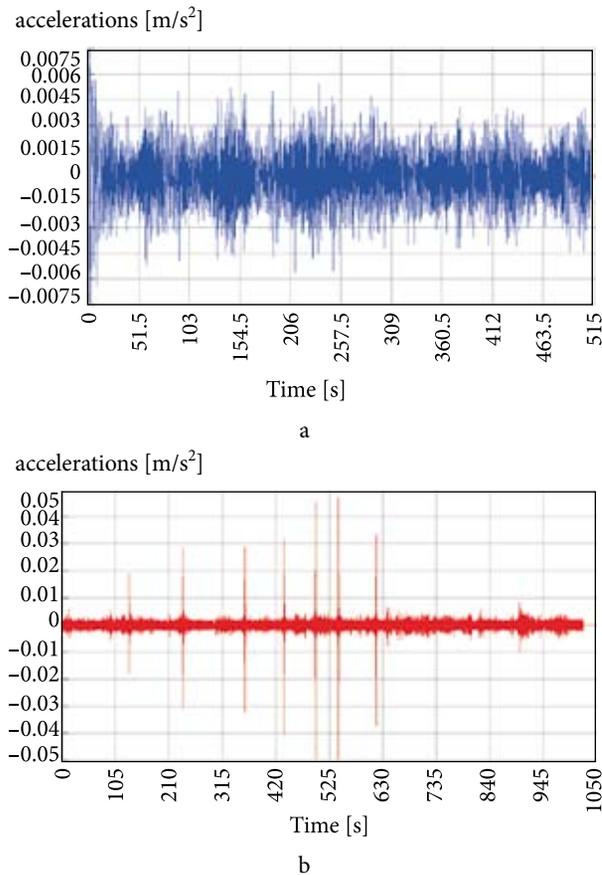


Fig. 5. The accelerograms obtained by using the 3rd sensor (in horizontal direction, at the level of 21.7 m) for two typical city traffic stages: a) conventional city traffic; b) a heavily loaded truck moving trough a localized road surface irregularity

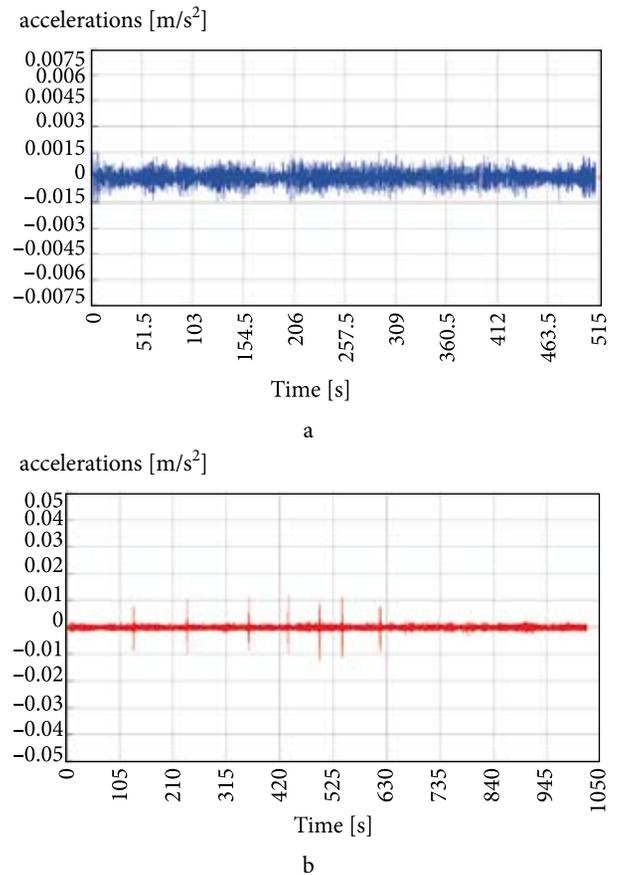


Fig. 6. The accelerograms obtained by using the 9th sensor (in vertical direction, at the level of 7.80 m) for two typical city traffic stages: a) conventional city traffic; b) a heavily loaded truck moving trough a localized road surface irregularity

caused by conventional city traffic. It reflects the background dynamic effect (usual vibration level) to the building structures. In this case, the acceleration value does not exceed 0.002 m/s^2 .

Fig. 6 b presents the histogram of accelerations in the same direction and at the same level but it is caused by a heavily loaded truck running seven times over a localized artificial road surface irregularity. The recorded seven peaks of accelerations show that the dynamic effect of heavily loaded trucks on the Belfry's vertical 'jumping' at the level of 7.8 m is by about 6 times higher compared to usual vibration level and reaches 0.0120 m/s^2 .

5. Analysis of Results and Discussion

The results of the presented measurement allow us to discuss findings them and drawing the appropriate conclusions.

The graph in Fig. 7 illustrates horizontal peak acceleration at the various altitudes of the building (in the direction perpendicular to Sventaragis street) caused by a heavily loaded truck moving through a localized road surface irregularity and conventional city traffic respectively.

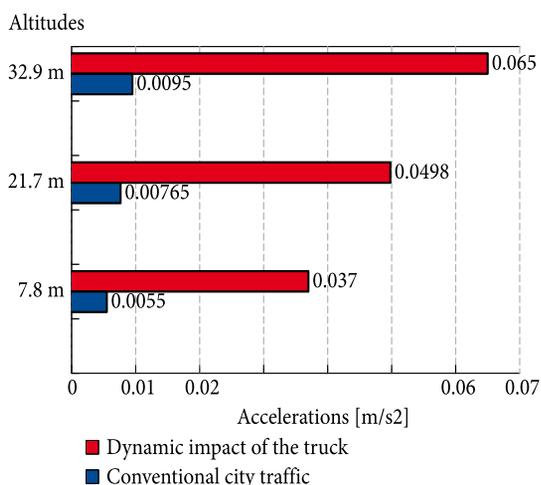


Fig. 7. The distribution histogram of horizontal accelerations along the vertical axis of the Belfry accelerations [m/s²]

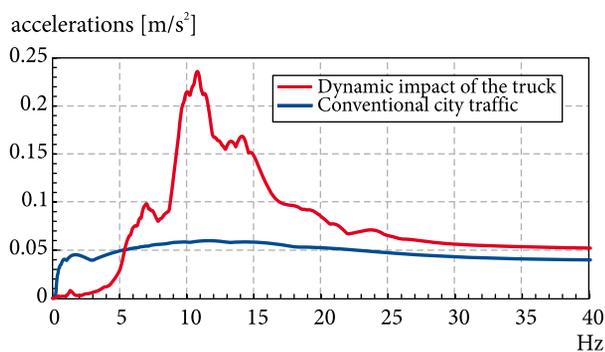


Fig. 8. The response spectra of the Belfry's accelerations obtained using the 3rd sensor (in horizontal direction, at the level of 21.7 m) for two typical transport traffic stages (with 5% damping)

In the case of conventional city traffic, the acceleration values (usual vibration level) do not exceed 0.01 m/s^2 . According to Polish code PN-85/B-02170 (having no Lithuanian equivalent), it may be stated that dynamic loads are insignificant.

However, while the heavily loaded truck was moving through a localized road surface irregularity (dynamic impact), the acceleration values were much higher: at the 4th floor level (7.80 m) – 0.037 m/s^2 while at the 7th floor level (32.9 m) the value increased up to 0.065 m/s^2 . According to Polish code PN-85/B-02170, it may be stated that in this case, dynamic loading may be dangerous for the structures considered.

The processed investigation data describe the harmful effects of traffic in absolute values. They allow us assessing the performance of the particular parts of the building as well as determining damages. Moreover, based on the analysis of the graphically presented results, it is possible to detect new damages in the structures of a building.

In order to determine the dynamic effects, the measured accelerations time histories were transformed to frequency domain (Clough 1993). Acceleration response spectra were calculated by using a commercial software package DynaTool (version 4.1.1). The tools provided are based on those used for structural analysis; however, they are based on Standard techniques and may be used in other branches of time and frequency analysis.

Two resonance frequencies were identified. The first resonance occurring at $\sim 1.3 \text{ Hz}$ can be attributed to the natural frequencies of the building structures while the second resonance frequency of $\sim 10.8 \text{ Hz}$ is attributed to the influence of the traffic.

6. Conclusions

The experimental analysis of Vilnius Arch-Cathedral Belfry allows us to draw the following conclusions:

1. Dynamic behaviour was investigated on the basis of the measured time history of accelerations. It was found that the impact of dynamic loading of the heavily loaded truck may be up to 7 times higher than dynamic loading caused by conventional city traffic.

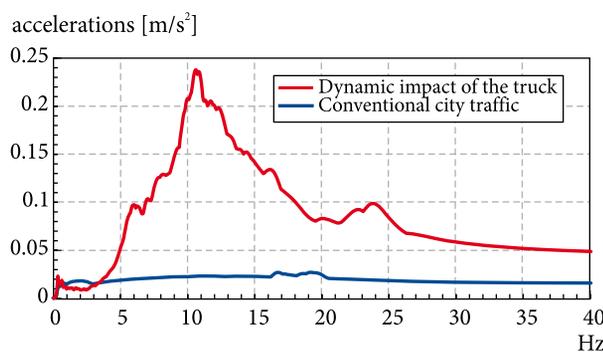


Fig. 9. The response spectra of the Belfry's accelerations obtained by using the 9th sensor (in vertical direction, at the level of 7.80 m) for two typical city transport traffic stages (with 5% damping)

2. The details of dynamic effects were described in terms of the response spectra of accelerations. Two resonance frequencies were identified. The first resonance occurring at the frequency of ~1.3 Hz can be attributed to the natural frequencies of the building structures while the highest resonance frequency of ~10.8 Hz is attributed to the influence of city traffic.
3. According to Polish code PN-85/B-02170 (having no Lithuanian equivalent), it may be stated that the influence of traffic-induced dynamic loading on the behaviour of the Belfry's structures is insignificant. Dynamic loading caused by the heavily loaded truck results in accelerations reaching 0.065 m/s^2 and may be dangerous for the structures considered.
4. The effective regulation of transport routes and the appropriate maintenance of the road surface in Vilnius Old Town and other districts may essentially decrease dynamic loading caused by traffic.
5. To ensure the effective maintenance of the Belfry's structures, a system of monitoring transport induced dynamic effects and their consequences could be recommended.

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