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# A MONUMENT OF HISTORICAL HERITAGE – VILNIUS ARCHCATHEDRAL BELFRY: THE DYNAMIC INVESTIGATION

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**Abstract**. The dynamic investigation of a monument of historical heritage – Vilnius Archcathedral Belfry – is investigated. In 2002 six new bells were installed in Vilnius Archcathedral Belfry according to a modern location scheme and their ringing order was changed. Evidently, they caused different dynamic loads which were not completely controlled and their effect on historical buildings of the Old Town of Vilnius could hardly be predictable. The paper presents the results of dynamic investigation of the Archcathedral Belfry, subject to the influence of the bell system operation. The dynamic impact was evaluated by measuring the acceleration history under the conditions, when different combinations of bells were used. A contribution of the dynamic effects was assessed in terms of response spectra. The obtained results have been thoroughly analysed and the appropriate findings and conclusions provided.

**Keywords:** dynamic analysis, building structures, historical heritage, dynamic load, response spectra, bells, experimental measurements.

## 1. Introduction

When Lithuania regained independence in 1990, Vilnius again became the capital of the independent state. In December 1994, a historical centre of Vilnius – the Old Town – was included into the UNESCO World Heritage List. Rapid revitalisation of the Old Town started in 1998.

In the period of revitalization and rehabilitation of the Old Town as the historical nucleus of the city, an exceptional attention was given to emphasize the role of the Old Town as an important international cultural centre in order to bring the revitalization process to the international level.

Along with routine reconstruction of various buildings, special attention was devoted to rehabilitation of buildings, listed as monuments of historical heritage of Vilnius. The Belfry of the Vilnius Archcathedral Basilica belongs to the most valuable monuments of the historical heritage of the Old Town.

In all countries valuable historical monuments are protected by special laws, while their technical state is checked periodically, and their reliability, strength and resistance to various environmental and human inflicted effects are predicted (Witzany, Cejka 2007a, 2007b; Calio *et al.* 2003; Sofronie 1999). The structural health monitoring is traditionally considered as observation of the behaviour of the structure over time. The technique is based on consolidated technologies of dynamic characterization and identification of the structures.

Various theoretical and experimental investigations of the influence of the dynamic loads caused by city traffic, operation of the bells, earthquakes, etc. on the resistance and reliability of structures of cultural heritage have shown the significance of the problems under consideration. Here, different approaches and techniques of strengthening the structures of cultural heritage are offered (Sofronie *et al.* 1999; 2000, 2003), full−scale testing and FEM analysis are used in 2004; main tools of dynamic investigation (Ciesielski, Stypula 2004; Stypula 1984a, 1984b; Niederwanger *et al.* 1997; Gentile *et al.* 2002; Podesta *et al.* 2007; Jaras *et al.* 2006) are applied.

Apart from natural and artificial damages of the structure considered, a new source of trouble emerged in 2002, when a new bell system was installed. The paper presents the results of dynamic investigation of the Archcathedral Belfry, subjected to the influence of the operation of the bell system. The dynamic impact was evaluated by measuring the acceleration history under the conditions, when different combinations of bells were used. A contribution of the dynamic effects was evaluated in terms of response spectra. The most dangerous operating conditions were also identified.

The paper is organized as follows: some historical facts and revitalisation steps are presented in Section 2, the Belfry structure and its bell system are described in Section 3, dynamic investigation and measurement technique are presented in Section 4, investigation results and discussion are given in Section 5, and conclusions are provided in Section 6.


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## 2. Historical development of the old town and revitalisation

Vilnius was first mentioned in European written sources in 1323 as the capital of the Great Duchy of Lithuania. The development of the city is related to several historical periods.

The historical nucleus of the Vilnius city – Old Town – was founded and developed on the confluence of the rivers Vilnia and Neris. Vilnius started exactly where the Vilnia flows into the Neris, while as early as the 5–6th cc. this was the location of a large Baltic settlement.

In the 14th c. the growth of the city was constrained by the attacks of the Order of Teutonic Knights. The 15th c. saw the construction of numerous Gothic brick buildings, as well as setting up and growth of monasteries and guilds, which significantly changed the outline of the city (Lietuvos architektūros istorija 1987; Drėma 1991).

After the Great Fire of 1471 new streets were built and, in 1503–1522, a five-gate defence wall was erected, enclosing the most densely populated part of the city and protecting it from possible Tartar invasions. Covering over 300 ha, the city nucleus was developed in the valley to the south of the Vilnia and Neris confluence. After the third and last division of the Lithuanian-Polish state in 1795, the major part of Lithuania, including its capital Vilnius, passed to Russia, and Vilnius became the centre of the Governor General's province.

Early in the 20th century, Vilnius lost its significance as an administrative centre. This period saw only limited construction in the Vilnius Old Town. The year of the World War II was a real disaster to the Old Town. Nearly 40 % of buildings were destroyed. During the soviet period after the war the Vilnius Old Town was partially renovated, however, more than 25 % of buildings had never been rebuilt – they were later replaced by open spaces and squares (Drėma 1991). Only the selected historical monuments were renovated.

Despite the significant losses, the Old Town remains an important centre of Eastern Europe and attractive place for visitors. In 1994, the world recognised the experience of Lithuanian specialists and the progress in the Old Town management took place by including the historic centre of Vilnius into the List of Sites of the World Heritage.

The Vilnius Old Town Revitalisation Strategy was developed in 1996. It involves different measures for protection, maintenance and conservation of individual buildings of historical and cultural value and even of their architectural and structural elements (Kačianauskas *et al.* 2004).

In co-operation with the state institutions, plans for both routine and preventive measures and sources of the appropriate funds for improving the protection of the heritage will be prepared within the framework of the Old Town strategy.

The most important projects are the reconstruction of the Royal Palace and the Archcathedral Square (Fig. 1).

**Fig. 1.** The Vilnius Archcathedral with the Belfry

## 3. Cathedral Belfry and its bell system

The most important and prominent building in the Old Town is the Archcathedral Basilica with the Belfry beside (Fig. 2a). The lower part of the Belfry is quite different from the rest of the building. In fact, it is much older, and in its original incarnation was one of the defensive towers of the Lower Castle (Lietuvos architektūros istorija 1987). The upper structure was built several ages later and, thus, a defensive tower was transformed into the Belfry. After a few reconstructions, it acquired the present form, which had not changed until 1893.

The structure of the building is schematically shown in Fig. 2b. It reflects two historically different parts having quite different geometry and construction styles.

The lower part, having a slightly non-symmetric annular cross-section with the external diameter ranging from 12.6 to 12.1 m and 3.0 or 2.0 m thick walls (Fig. 2c), is made of stone masonry. It is 11.9 m high and has four floors. The top of this building part was later covered by cast-in-place joist ceiling, which was constructed as a stiffened reinforced concrete slab.

The upper part of the building (Fig. 2d) has an octahedral cross-section with the characteristic diameter ranging from 11.4 to 9.9 m and 1.5, and 1.3 m thick brick masonry walls. The wall of the upper part is weakened by a number of window openings. The upper masonry structure is 25.5 m high. The Belfry roof is a light timber dome structure covered by a thin copper shell. The total height of the building is about 56 m.

The first bells were hung in the Belfry as early as 17-th century, while later (18th c.) the number of bells was increased. This set of bells is still operating. However, in 2002 six new bells – "Jurgis Matulaitis", "Anna", "Helena", "Stanislaus", "Casimirus", "Joachim" (Fig. 3), with their masses, ranging from 475 kg to 2600 kg, were installed, according to a modern location scheme (Fig. 4). Their operating order was changed respectively.

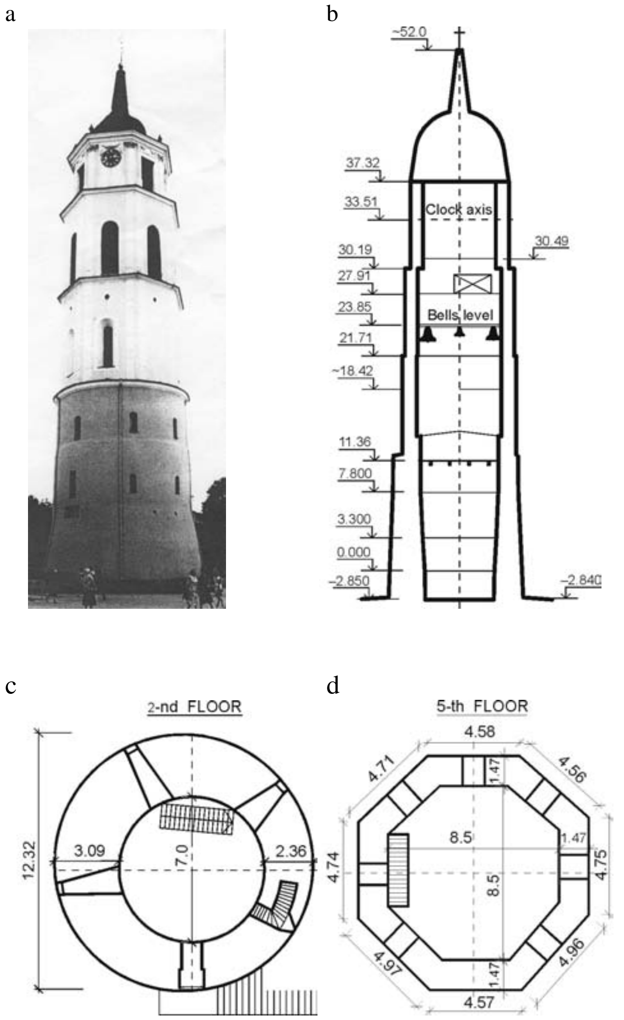


**Fig. 2.** The Belfry's geometry: a – a general view; b – vertical cross section; c – horizontal cross section of the lower part; d – horizontal cross section of the upper part

**Fig. 3.** The biggest bell "Joachim" and its wooden support

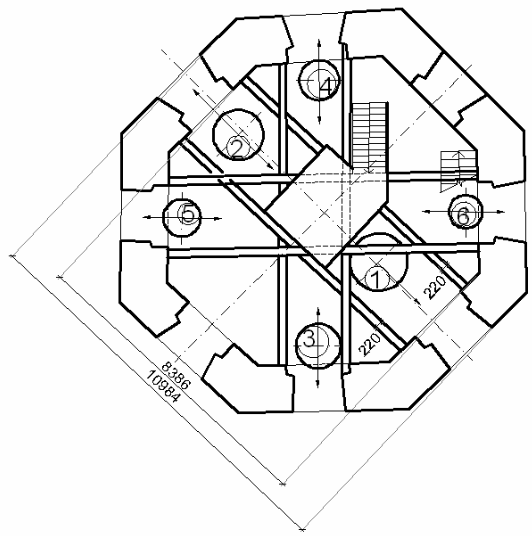


**Fig. 4.** The location scheme of the bells on the 6th floor

The explicit technical data on the bells are given in Table 1.

**Table 1.** Technical data on the bells

| No | Name of the bells | Sound tone | Diameter | Mass |
|---|---|---|---|---|
| 1 | **Joachim** | $h^o$ | 1580 mm | 2600 kg |
| 2 | **Casimirus** | *d'* | 1380 mm | 1600 kg |
| 3 | **Stanislaus** | *e'* | 1230 mm | 1150 kg |
| 4 | **Helena** | *fis'* | 1100 mm | 800 kg |
| 5 | **Anna** | *g'* | 1030 mm | 675 kg |
| 6 | **J. Matulaitis** | *a'* | 920 mm | 475 kg |
| | | | | Total: 7300 kg |

## 4. Dynamic investigation and measurement technique

There are two most critical factors reducing the ability of building structures to retain their original properties and serviceability. Natural long-term degradation of the materials under the exposure to the environment, which nowadays is often aggressive, is referred to the first category. Short-time dynamic actions, such as vibrations or impact loads, may be considered the second even most dangerous factor.

Dynamic investigation of the structures based on the advanced measurement technique and computer-aided technologies seems to be one of the most powerful research tools to be applied to evaluating the dynamic effects. On the other hand, dynamic methods have been extensively applied to assessing damage, including long-term damage of structures and structural members (Ciesielski, Stypula 2004; Stypula 1984a, 1984b; Niederwanger *et al.* 1997; Gentile *et al.* 2002; Podesta *et al.* 2007; Clough 1993).

Dynamic investigation is mainly aimed at determining the influence of the dynamic loads imposed by bells and ways of reducing harmful effects.

This paper focuses on the operation of the bell system installed during the last reconstruction in 2002. The new bronze bell system, including 6 massive bells, was placed at the sixth floor level of the Belfry, 26 m above the ground level. The new bells were provided with 3 supporting frames, located at an angle of approximately $60^0$ to each other (Fig. 4). Each frame carries two bells. The balance of the bells is upset by electric motors and they begin to swing about a horizontal carrying axle until hitting against a vertical bar and starting to ring (Fig. 3).

This new bell system caused an intense local vibration on the $6^{th}$ floor and the whole tower building, leading to cracking of a masonry structure.

The performed dynamic investigation aimed to capture both global and local behaviour of the Belfry building, affected by dynamic loading caused by the operation of the bells (Kliukas *et al.* 2004). The region of the global behaviour was limited, however, by the brick masonry structure to the altitudes of 11.90 m and 32.90 m, while the region of local behaviour was limited to the altitudes of 21.7 m and 32.90 m. This region is highly affected by the bells operation. In addition, it is suffering from the accumulated environmental degradation of a long-term nature. Since the bells on wooden portals are hung in pairs 1–2, 3–4, 5–6 (Fig. 4), the above arrangement of the bells may significantly increase the dynamic effect on the Belfry structures, when a particular pair of bells is operating.

During the dynamic experiment, a mobile set of oscillation measuring devices was used to register vertical and horizontal oscillations caused by the bell operation. The equipment consisted of:

- portable multifunctional analysis system "PULSE – 3560C" (12 canals), with software 7700&7705. Producer "Bruel & Kjaer" (Denmark);
- 12 one-directional sensors (accelerometers) of the type 7752. Producer "Endevco" (USA);
- standard portable personal computer "Hewllet Packard".

The directional vibrosensors were rigidly fixed to the structural elements of the Belfry, according to purposeful layout schemes (Fig. 5).

**Fig. 5.** Accelerometer in the working position

The dynamic experiment, using the analytical system "Pulse-3560C", includes the layout of sensors in typical measurement directions at the floor levels as well as distribution of sensors along the vertical axis of the belfry.

Basic data on sensors layout are given in Table 2. Here: 1) accelerometers 4, 8, 9, 10, 11, 12 are placed at the floor level; 2) altitudes [m] are measured at the $2^{nd}$ floor level; 3) V – vertical, H – horizontal.

**Table 2**. The layout of accelerometers

| Number of accelerometers | Direction of measurement | Altitude [m] | Location of accelerometers |
|---|---|---|---|
| **II-1** | V | –2.82 | In Šventaragis str. |
| **II-2** | H | –2.82 | In Šventaragis str. |
| **II-3** | H | 32.86 | In the clock niche ($7^{th}$ fl) |
| **II-4** | H | 21.71 | In the window niche ($6^{th}$ fl) |
| **II-5** | H | 14.50 | On the $5^{th}$ floor niche, 40 cm up |
| **II-6** | H | 32.86 | In the clock niche ($7^{th}$ fl) |
| **II-7** | H | 14.40 | On the $5^{th}$ floor niche, 40 cm up |
| **II-8** | H | 21.71 | In the window niche ($6^{th}$ fl) |
| **II-9** | V | 7.80 | In the window niche ($4^{th}$ fl) |
| **II-10** | H | 7.80 | In the window niche ($4^{th}$ fl) |
| **II-11** | V | 7.80 | In the window niche ($4^{th}$ fl) |
| **II-12** | H | 7.80 | In the window niche ($4^{th}$ fl) |

## 5. Measuring results and discussion

The dynamic experiment comprises four Belfry mass acceleration measurements according to the following modes of operation:

1) the bells operate separately, ringing one after another in a consecutive order;
2) the bells operate all together;
3) four smaller bells operate together;
4) two biggest bells operate together.

The signal registering step of each measurement is $7.8125\times10^{-3}$ s, while the measurement time-span ranges from $3.839922\times10^{2}$ to $6.399922\times10^{2}$ s. The explicit data on measurements are in Table 3.

With the aim to eliminate the influence 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).

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

**Table 3.** The basic data on dynamic measurements

| Measurement No | Period of measurement [s] | Registration step [s] | Points number |
|---|---|---|---|
| **I** (running bells) | 0÷6.399×10 $^{2}$ | 7.8125×10$^{-3}$ | 81919 |
| **II** (all together) | 0÷5.039×10 $^{2}$ | 7.8125×10$^{-3}$ | 64511 |
| **III** (4 bells) | 0÷5.119×10 $^{2}$ | 7.8125×10$^{-3}$ | 65535 |
| **IV** (2 bells) | 0÷3.839×10 $^{2}$ | 7.8125×10$^{-3}$ | 49151 |

In the present investigation, histograms of peak accelerations of each measurement were attached to each point considered. They provide the information about the dynamic effect produced by bells operating in various modes and its distribution and localization in the Belfry's structure.

The average values of only one measurement parameter (acceleration), allowing us to determine the harmful effect of particular modes of the bell operation on the Belfry structure is presented in the article. The comparative analysis of the effects produced by the bells operating in various modes was performed in the present investigation, based on the indication of the 8$^{th}$ sensor, whose data reflect a dangerous effect (Fig. 6).

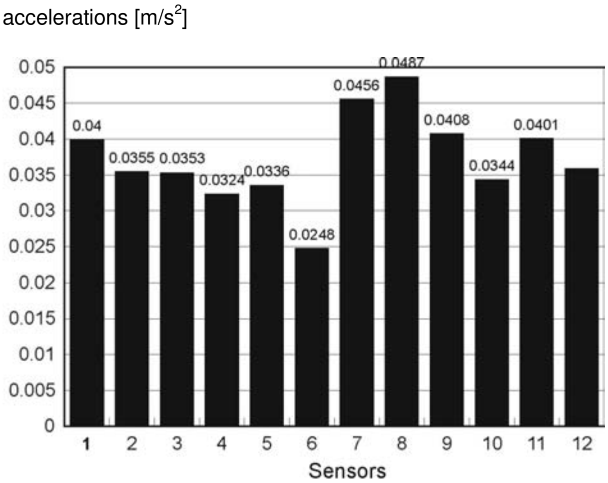


**Fig. 6.** The peak values of accelerations obtained by different sensors

In Fig. 7, acceleration time history of the most characteristic (8$^{th}$) sensor is presented on the same scale. It reflects the situations when the bells are ringing one after another, all at the same time, 4 smaller bells, or 2 biggest bells at the same time. Fig. 7a presents the histogram of the effect (acceleration) on the building structures produced by each of 6 bells ringing one after another sequentially. It shows that the effect of the bells on the acceleration value is different (because their mass differs by about 3 times), ranging from 0,0084 m/s$^2$ to 0,0248 m/s$^2$.

While the bells operate all together (Fig. 7b), the peak acceleration value (in modulus) at the same level is 0,0278 m/s$^2$. It is smaller than the value characterizing the operation of the 2 bigger and 4 smaller bells.

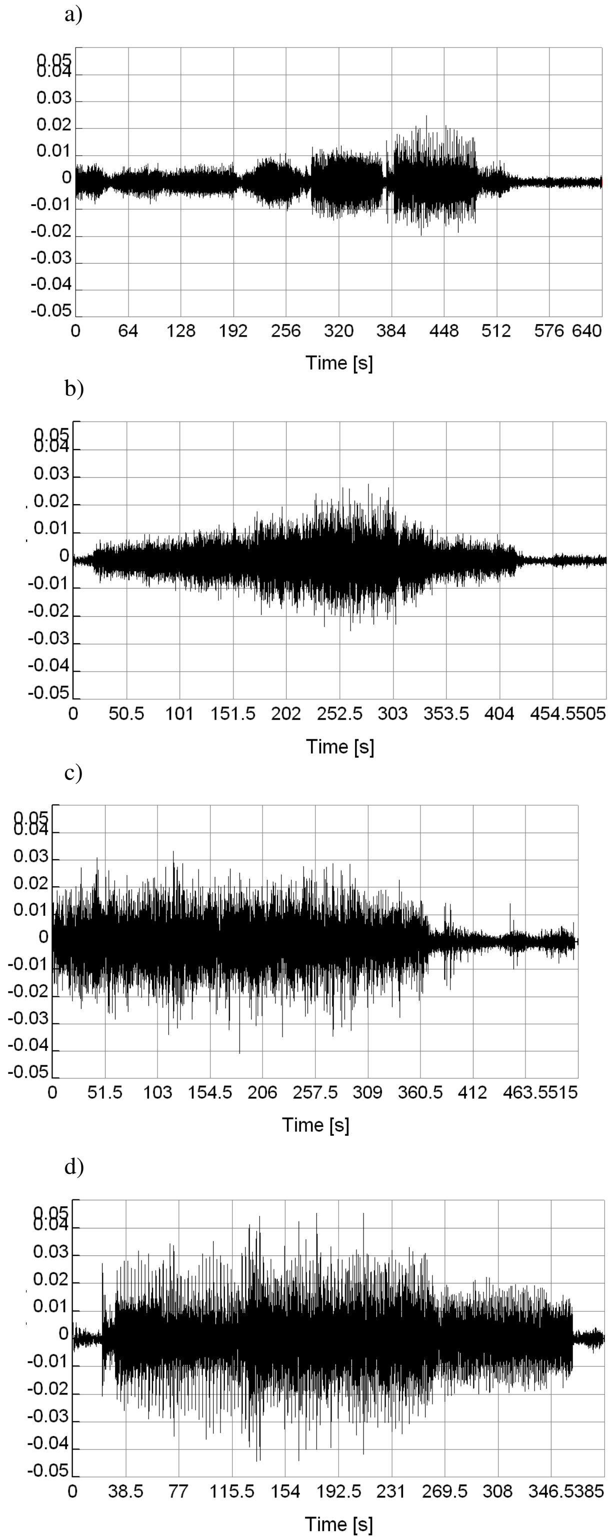


**Fig. 7.** The accelerograms obtained by using the 8$^{th}$ sensor for different operating modes of the bells: a – the bells operate separately one after another; b – the bells operate all together; c – 4 smaller bells operate together; d – 2 biggest bells operate together

As shown in Fig. 7 c–d, when 4 smaller bells are operating at the same time, the maximum acceleration is 0,04086 m/s$^2$, while for two larger bells operating together it reaches 0,04532 m/s$^2$. This can be accounted for the fact that, when all the bells are operating at the same time, they suppress the acceleration effect of building oscillations and, thereby, the amplitudes, produced by each of them.

The presented results and simple comparison show that the operating mode of two biggest bells is the most dangerous.

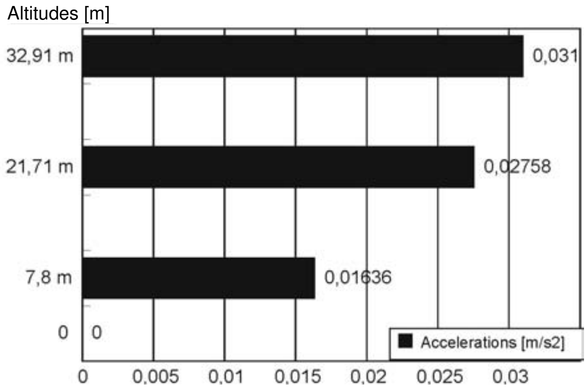


**Fig. 8.** The distribution histogram of accelerations along the vertical axis of the Belfry, while the bells operate all together

The graph in Fig. 8 illustrates accelerations at various altitudes of the building, when all the bells are ringing at the same time.

At the top level, the acceleration values reach 0,031 m/s$^{2}$, while farther from the operating bells (when the stiffness of the building structures is higher), the acceleration values decrease.

Based on the investigation results, two Belfry zones, where the bells operation and other factors present danger to the the building, were identified: a local zone found between the 5$^{th}$ and 7$^{th}$ floors (height 25–32 m) and a global zone located between the 4$^{th}$ and the top floor (height 10–37 m). In the local zone, gradual destruction of the walls can be observed, with disintegration of the supporting elements of a wooden portal, where the bells hang. In the global zone, the number of damages caused by the bell operation, traffic and harmful environmental effects is continually growing. Therefore, long-term monitoring of the Belfry structures and fixing the defects and changes can be recommended.

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

In order to determine the dynamic effects, the measured acceleration time histories were transformed to frequency domain (Clough 1993). The acceleration response spectra were calculated by using a commercial software package DynaTool (Fig. 9). The tools provided are based on those used for structural analysis; however, they are based on standard techniques and will be used to other branches of time and frequency analysis.

The first resonance occurring at 1,25 Hz is attributed to natural frequencies of the building structures. Two further resonance frequencies 13,7 Hz and 22,8 Hz are attributed to the influence of the bell system produced by the operation of 4 smaller and 2 bigger bells, respectively.

## 6. Conclusions

The experimental analysis of the Vilnius Archcathedral Belfry allows us to draw the following conclusions:

1. The dynamic behaviour was investigated on the basis of the measured time history of acceleration. It was found that the largest acceleration occurs in the wall section oriented along the movement of the two largest bells (8$^{th}$ sensor).

2. The most dangerous dynamic effects of high acceleration magnitude are produced by the two largest bells "Joachim" and "Casimirus". The investigation has shown that accelerations in the areas where the bells supports are fixed, exceed the ultimate value of 0.1 m/s$^2$, reaching 0.8…1.0 m/s$^2$. The operation of the bells causes the destruction of the Belfry wall.

3. Details of dynamic effects were described in terms of the response spectra of accelerations. Three resonance frequencies were identified. The first resonance occurring at 1,25 Hz can be attributed to natural frequencies of the building structures. Two further resonance frequencies 13,7 Hz and 22,8 Hz are attributed to the influence of the bell system, i. e. the operation of 4 smaller and 2 bigger bells, respectively.

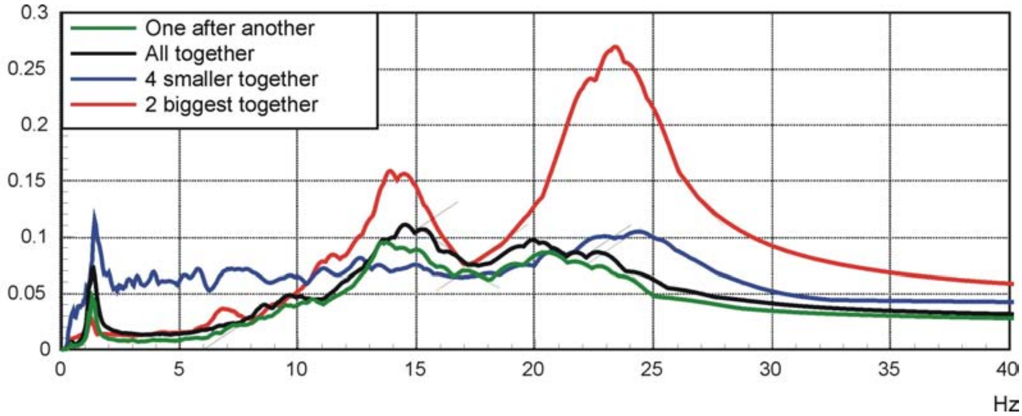


**Fig. 9.** Response spectra obtained for different loading systems (with 5 % damping)

4. Long-term monitoring of the structures of Vilnius Archcathedral Belfry and their defects and changes have not been performed. To ensure the effective maintenance of the Belfry structures, a system of monitoring of the structures and their defects allowing us to detect the changes in building performance should be developed.

**Acknowledgement**

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**VILNIAUS ISTORINIO PAVELDO PAMINKLO – ARKIKATEDROS VARPINĖS – DINAMINIAI TYRIMAI**

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S a n t r a u k a

Nagrinėjamas Vilniaus arkikatedros varpinės eksperimentinis tyrimas nuo dinaminių apkrovų, sukeltų veikiant varpams. Preliminaraus tyrimo metu varpinės sienų konstrukcijose buvo pastebėta irimo požymių, daugybinių plyšių. Tai sukėlė ilgalaikis statinio eksploatavimas. Tačiau 2002 m. pagal naują schemą varpinėje pakabinus 6 naujus varpus labai pasikeitė jų poveikis statinio konstrukcijoms. Skambant varpams sukeliamos dinaminės apkrovos varpinės konstrukcijoms iki šiol dar nebuvo tyrinėtos. Atliktas dinaminis eksperimentas, kurio metu ištirti varpinės charakteringųjų vietų masių pagreičiai nuo įvairiais režimais skambančių varpų: varpai skamba vienas paskui kitą iš eilės; skamba visi varpai kartu; keturi mažieji varpai skamba kartu; skamba tik du didieji varpai. Dinaminis poveikis statinio konstrukcijoms įvertinamas pagreičių atsako spektrais. Gauti rezultatai kruopščiai apdoroti ir pateiktos išvados.

**Reikšminiai žodžiai:** eksperimentinė analizė, kultūrinis paveldas, dinaminė apkrova, masių pagreičiai, atsako spektras, varpai, eksperimentiniai matavimai.

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