Application of vibroacoustical methods for testing and condition monitoring of historical buildings in St.-Petersburg

A. Ionov, A. Pyshin & V. Chizov
Acoustics Division, Krylov Shipbuilding Research Institute, Russia

Abstract

An experience of vibroacoustical methods application for testing and monitoring of historical buildings in St.-Petersburg is described. Researches in the Smolny Cathedral and Rumyantsev’s Palace founded in the XVIII century are considered. The results of vibration measurements and analysis of Rumyantsev's Palace and an adjacent embankment are presented. It is shown that the obtained spectral and statistical vibration characteristics provide the possibility to estimate the building damage rate and the vibration load induced by the embankment traffic.

In the case of the Smolny Cathedral it is shown that numerous reconstructions of internal decorations have essentially changed acoustical properties of its main hall. The results of the Smolny Cathedral reverberation time measurements at the present and 10 years ago are presented. Changes of the cathedral reverberation time frequency dependence due to reconstructions are discussed. Recommendations aimed at further improvement of the cathedral acoustical properties and renewal of the internal appearance are formulated.

Introduction

Vibroacoustical investigations serve as a reliable method for control and monitoring of the condition of historical buildings. They have two distinctive features. They do not damage historical buildings and have low costs. The procedure of vibroacoustical measurements is constantly updated and automated. In this paper the description of researches carried out in two historical buildings in St.-Petersburg is presented. They are vibration measurements and analysis of Rumyantsev's Palace and acoustical investigations in the Smolny Cathedral.
Analysis of Rumyantsev's Palace condition

Rumyantsev's Palace is located on the English Embankment not far from the Lieutenant Smidt Bridge. It is exceptional among nearest buildings by a large twelve-column portico (Figure 1). The building was found in 1725. In 1802 Earl Rumyantsev bought the merchant house on the river Neva embankment. In 1826 the portico decorated by a triangle pediment was attached to the main building. After Earl Rumyantsev's death the palace according to his will became a museum for his book, coin and medal collections. At the present Rumyantsev's Palace is the city history museum. During numerous reconstructions some internal walls were removed. This has weakened the facade wall strengthening. Moreover, portico and building foundations were practically disconnected. Long-term nonuniform soil settlements have caused a small turn of the portico foundation and a visible slope of the columns. During the recent 10 years this process was significantly accelerated due to heavy traffic along the palace facade. It has increased vibration of building elements and the pavement. Vibration promotes soil particles carry-over from under the foundation base.

Vibrational investigations were carried out in September 1996. They had to evaluate real condition of Rumyantsev's Palace building and determine the effect of vibration induced by the traffic along the palace on the character of deformations suffered by elements of the building and the portico. The measurements were fulfilled according to international standard [1]. Vibration
levels at different points of the palace facade wall, the portico bottom tier wall and the column shafts and bases were determined. Multipoint measurements have allowed determining reciprocal displacements of the palace structural elements.

Measurements have shown that the vibrational load on the building has an unsteady character. While lorries pass the palace building, the vibration level of the pavement close to the portico might increase by 30 dB. The values of vibration acceleration might reach $20 \pm 30 \text{ mm/s}^2$.

A typical vibration acceleration spectrum dependence measured at the base of one of the portico columns in horizontal and vertical directions is shown in Figure 2 (the reference level is $3 \times 10^{-4} \text{ m/s}^2$). Vibration acceleration values were averaged over 5 minutes in daytime at the maximum intensity of traffic along the palace building. The spectral values of vibration levels in horizontal and vertical directions are close to each other. At frequencies of $2 \pm 4 \text{ Hz}$ the first strongly marked resonance of the portico oscillation takes place. Multipoint measurements of vibration levels have shown that at frequencies of $3 \pm 10 \text{ Hz}$ the portico bottom tier oscillates as a rigid body. At frequencies of $2 \pm 4 \text{ Hz}$ the portico and the palace facade wall oscillate together as a single whole. In this frequency range their vibration level values are close to each other, but they drastically differ at higher frequencies. The portico bottom tier and the building facade wall oscillate independently at frequencies of $10 \pm 50 \text{ Hz}$. This confirms the earlier suspicion about weak bond between portico and building foundations. Vibration levels values of the different building facade wall elements are essentially different. The difference might reach the value of $10 \pm 15 \text{ dB}$. This is the evidence of the facade wall integrity damage. Vibration measurements made for the every portico columns have shown that all columns are in a satisfactory condition.

![Figure 2: Vibration acceleration spectrum measured on the base of one of the portico columns of Rumyantsev's Palace in vertical and horizontal directions.](image-url)
Measurements have shown that the vibration level of building elements essentially depends on the intensity of traffic along the palace. The statistic analysis of vibration level time realizations was fulfilled. Probability distribution functions of vibration acceleration values at different time of the day are presented in Figure 3. The duration of building facade wall vibration measurement for each realization was 25 minutes. The most probable values of the building facade wall vibration acceleration essentially depend on the daytime, i.e. the intensity of traffic. The most probable daytime vibration level is 9 times greater than at night and reaches 10 mm/s². In order to reduce the destructive vibration effect on Rumyantsev's Palace it is necessary to reduce the intensity of traffic along the English Embankment. For this purpose vehicle speed near Rumyantsev's Palace should be restricted or lorries should be forbidden to drive along the embankment. Another way to reduce vibrations of the palace building elements and to strengthen its structure could be to underpin portico and building foundations.

**Acoustical investigations in the Smolny Cathedral**

The Smolny Cathedral is one of the most beautiful temples in St.-Petersburg. Construction of the Smolny, or to be more precise the Resurrection, Cathedral was started in 1748. It was the most Russian creation of an Italian count Bartolomeo Rastrelli, the court architect of Empress Elizabeth, daughter of Peter the Great. Paradoxically, big services have almost never been held at this one of most beautiful churches of St.-Petersburg. For the whole of the last century the temple has been the domestic church of the Institute of Noble Spinster. Today the Smolny Cathedral is a State Concert & Exhibition Hall. Its musical repertoire...
includes symphonic and folk performances, concerts of the State Chamber Choir of the Smolny Cathedral.

The Smolny cathedral has a two-tier base portion that expands into a high drum of the central dome. Four two-tier belfries cluster around the central drum (Figure 4). The height of the base structure is about 30 metres. The drum diameter and height are 13 and 30 metres, respectively. The cathedral height is 94 metres; the floor area is about 3650 square metres. The total volume of the building is 110000 cubic metres. There are two big columns of 4 by 4 metres in cross-section placed in the central part of the cathedral. A high partition that imitates an icon-stand almost reaches the upper level of the second tier of the cathedral base structure. An unusual feature of the Smolny concert hall is that the audience seats occupy only a small part of the hall.

An assessment of sound reverberation time, clarity, definition and structures of sound reflections were carried out in the empty cathedral hall in summer 1999. Reverberation time measurements were made according to the ISO/DIN 3382 international standard [2] with use firing a sport signal pistol from the scene as a pulse signal.

The Smolny Cathedral reverberation time frequency function averaged over all measurement points is plotted in Figure 5. Reverberation time varies from 10.2 s at low frequency to 2.5 s at high. The reverberation time shows a very strong dependence on the frequency. It is almost 4 times greater at low frequency than at high. In concert halls with good acoustics and famous Russian churches the reverberation time does not change so sharply with frequency. A reverberation time of 10 s at low frequencies as in the Smolny Cathedral is too high for a concert hall. Reverberation time within the frequency range 500–1000 Hz is an usual characteristic for concert halls. The value 6.2 s reverberation time in the Smolny Cathedral at medium frequencies is too high for
musical performances, even taking into account the huge size of the temple. The optimum reverberation time for choir performances in Russian churches with volumes of the Smolny Cathedral is approximately 4 s (Makrinenko [3]). The medium-frequency reverberation time of the best European and American concert halls is 1.5–2.5 s (Reichart [4], Beranek [5]), i.e. one third that of the Smolny Cathedral.

The second curve in Figure 5 represents the results of Smolny Cathedral reverberation time measurements made in 1989. At the present moment the hall reverberation time values in the whole frequency range are lower than 10 years ago. This difference resulted from the hall reconstruction. During the Second World War the Smolny Cathedral was used as a hospital. Then the building was used as a storehouse, cinema and exhibition hall. Only in 1989 it was decided to use the Smolny Cathedral as the Concert and Exhibition Hall. After that the whole stone floor area was covered with a carpet. The windows of the base part of the cathedral structure were curtained. The cathedral walls were plastered A tall plywood box partition that imitates an icon-stand was installed. It has reduced the total volume of the main hall. All these changes have inserted additional acoustical dissipation into the hall, that reflects in reduction of reverberation time values at middle and high frequencies.

The Smolny Cathedral pulse response structures were studied. The structure of pulse response, i.e. sound of the shoot made from the scene and recorded in the audience hall, shows a small number of high-level reflections in the start portion. In the middle part the cathedral ceiling and side-wall reflections are delayed, but
at the same time there are no undesirable concentrations of late sound reflections which one perceives as an audible echo.

The results of acoustic measurements allow formulating some guidelines for the improvement of acoustic properties of the cathedral without altering its historical and architectural interior. Originally there were four beautiful large chandeliers in the cathedral. They have not survived and it might be worth to restore or reconstruct them. The chandeliers might be helpful in terms of sound reflection at low frequencies and direct late ceiling reflections to the audience. That would improve acoustical quality of the cathedral. By now the cathedral has lost icons and mural paintings. Their restoration or reconstruction would reduce the cathedral reverberation time and lead to improvement in the acoustical quality of the Smolny Cathedral.

Conclusions

Vibroacoustical methods can be used as a powerful tool for control and monitoring of historical buildings conditions.

An analysis of Rumyansev's Palace condition has shown that the causes of the building trouble are nonuniform settlement of the building base, mistakes made during design work and reconstructions and the effect of vibration induced by traffic along the palace facade. Vibrational investigations have given a possibility to clarify the pattern of Rumyantsev's Palace damage and formulate recommendations for its repair and maintenance. The acoustical measurements fulfilled in the Smolny Cathedral have demonstrated the possibility of qualitative estimation of long-term changes of the cathedral interior. They have enabled to formulate recommendations for the next reconstruction of the cathedral interior taking into account its acoustical properties.

References