Vibro-acoustic design of the stage floor reconstruction of a concert hall

F. Augusztinovicz[1], T. Kimpián[1,2]
[1] Budapest University of Technology, Department of Telecommunications
Budapest, Magyar tudósok krt. 2, Hungary
e-mail: **fulop@hit.bme.hu**
[2] current address: ThyssenKrupp Presta AG
Essanestrasse 10, FL-9492 Eschen, Liechtenstein
e-mail: **tibor.kimpian@thyssenkrupp.com**

Abstract

Due to the continuous and intensive use in the 100 years time period, the building of the Ferenc Liszt Academy of Music in Budapest is considerably aged. Beyond its deterioration it also lacks equipment and systems which are a must in modern cultural buildings, therefore it will undergo a total reconstruction. One of the most critical acoustic element of the reconstruction is the wooden stage floor construction, which should preserve its favourable acoustic properties while ensuring much more storage place hereunder, to be used for new logistic purposes. In order to determine the vibro-acoustic properties of the current system, an extended measurement series was performed and evaluated. Based on the extracted modal model a number of structural models were developed, updated and various design versions for the new structure compared. The paper reports on the tools, methods and most important results of the measurements and experiments, discusses the applied vibro-acoustic models and the used model reduction techniques, and presents the predicted characteristics of the final design.

1 Introduction

Founded by Ferenc Liszt, the Academy of Music is a real gem of today's Budapest. Opened in 1907, the building is one of the most beautiful fin-de-siècle music palaces of the continent, hallmarked by a number of structural and stylistic innovations of those times. Nevertheless, due to the continuous and intensive use in the 100 years time period the building is considerably aged and lacks equipment and systems which are a must in modern buildings, therefore it will undergo a total reconstruction. The aim of the works is to provide up-to-date circumstances for the music culture, education and concert life with the renovation of the building, keeping in view its historic values and, first and foremost, the greatly appreciated acoustics of the grand concert hall.

In the course of preparations of the renovation distinctive attention was paid to the restoration of stage construction, Fig. 1, which has to be newly rebuilt, with new stage technique installed. Nevertheless, the acoustical behaviour of the new stage may not differ much from the present one, which is regarded as very good both by musicians and audience alike. Therefore, an extended measurement series and subsequent analyses were planned and performed, in order to unravel the vibro-acoustic behaviour of the stage, to establish its most important parameters and to determine, which parts of the original structure have to be rebuilt in unvarying form and what can be changed, in order to meet the requirements of a recently built modern concert hall. This paper reports on the experiments and numerical simulations, performed on a selected part of the currently existing stage, as well as on some design variants of the new structure.

The current electronic version of the paper addresses the problems and gives a short overview of the applied tools and methods. The obtained results and details of the drawn conclusions will however be reported at the oral presentation of the paper.

Figure 1: The stage under investigation

2 Construction and characteristics of the original stage structure

The stage essentially consists of heavy timber trusses, supporting the floor which is also made of timber, see Figure 2. The bottom-up order of layers of the floor is the following: 10×15 cm timber cross beams, 5×15 cm purlins at app. 40 to 50 cm spacing, 4×12 cm floor planking and 2 cm oaken parquet, with 2-3 mm thick plastic damping layers below and above the planking. The trusses are fixed by U-straps and a few screws, the planking and the parquet nailed. Large parts of the trusses are still original, but about one-fourth of the trusses was replaced by steel beams and the planking and parquet was replaced in the course of a reconstruction in 1976-77.

Figure 2: Wooden constructions of the stage

The whole structure has got in bad state of repair by today. Quite a few beams and purlins are twisted and/or cracked, some of them supported or fixed by timber wedges while other ones have loosened in the course of time. Certain parts of the floor are rather solid, other parts however deflect a few cm when walking on the stage. Beyond its bad condition, the intention of the owner to ensure more storing place under the stage implies too that the stage has to be reconstructed. Nevertheless, musicians who regularly play in the concert hall have already got used to the stage, and there is general consent among them that the stage plays an important and favourable role in the outstanding acoustics of the hall.

In spite of this subjective evaluation, it is felt that the basic question of "how and to what extent does the stage floor contribute to the radiated sound of instruments" has to be investigated first, by using objective methods. More specifically, the following issues were raised:

- How does the stage floor behave? Does it work as a sound reflector, as a sound absorber, or perhaps both, to some extent?
- What is the frequency dependence of the acoustic characteristics?
- How do vibrations propagate in the supporting structure?
- If vibrations play an important role, does the stage floor act as a secondary sound radiator for instruments which are supported on the floor, or not?

After having answered all these questions satisfactorily, a better established decision can be made on what can be modified and what has to remain (better speaking: what has to be rebuilt according to the original design) of the stage floor, in order not to risk losing the currently very good acoustics.

3 Measurements on the stage

The vibro-acoustic characteristics of the stage floor were first investigated by means of an extended measurement series in the original condition of the hall, i.e., before the reconstruction works have commenced. The following measurement program was performed:

- measurements of vibration propagation in the trusses, by using both real-life and artificial excitation,
- measurements of vibration propagation in the stage floor,
- frequency response function measurements, referenced to force excitation: determination of point and transfer mechanical impedances as well as sound radiation,
- postprocessing of measured FRFs to derive eigenfrequencies, mode shapes and propagation damping values.

All these measurements were made along a 3 × 4.2 m section of the stage of 16.4 × 9.5 m, see in Fig. 3. Accelerometers were fixed to points of the trusses and floor, presumed to be the most revealing points of the structure. When selecting the measuring points we aimed to obtain sufficient information on the vibration propagation both vertically, downwards from the floor to the support, and horizontally, within the stage floor. As a result, a "wireframe" model of the investigated structure was obtained consisting of two main components.

The vibration propagation measurements were performed both by using an instrumented impulse hammer, a heavy medical ball and by real-life structure-borne excitation produced by a cello and a contrabass. Measurements were also made in the course of normal a concert given by a symphonic orchestra and opera singers. Eventually, eigenfrequencies and normal modes were extracted whenever possible.

4 Numerical simulations

The aim of numerical simulations was manifold:

- to derive a verified modal model of the selected structure of the stage (based both on measurements and structural calculations)

- to develop a coupled vibro-acoustic model, in order to investigate various sorts of fluid-structure interactions
- to give the best possible answers to the questions posed in Chapter 2
- to enable the designer to run various design versions of the new stage construction.

The structural analysis tool was NASTRAN, Ver.2005. The same section of the stage as selected for the experiments were used. It has turned out after the first set of calculations that a simple, isotropic model of the construction gives very poor results, hence an orthotropic model was developed and considerably better results found. This model was used for later investigations.

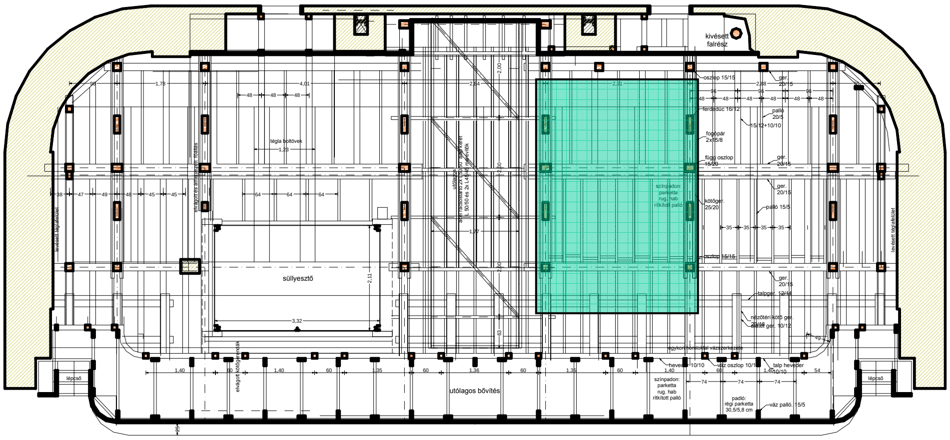

Figure 3: Section of the stage, selected for detailed investigations

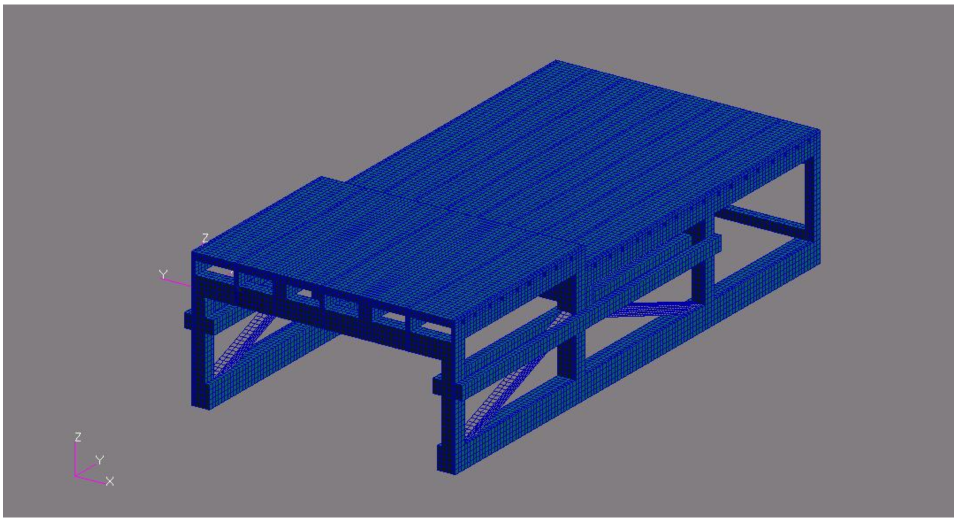

Figure 4: Structural model of the investigated stage section

In the second step of the modelling work the structural part was essentially reduced and a coupled structural FEM- acoustical BEM model was developed, see Fig. 5. This model was used to investigate both the sound radiation characteristics of the stage surface under well defined structural excitation, and the structural response of the system to a simplified acoustical input.

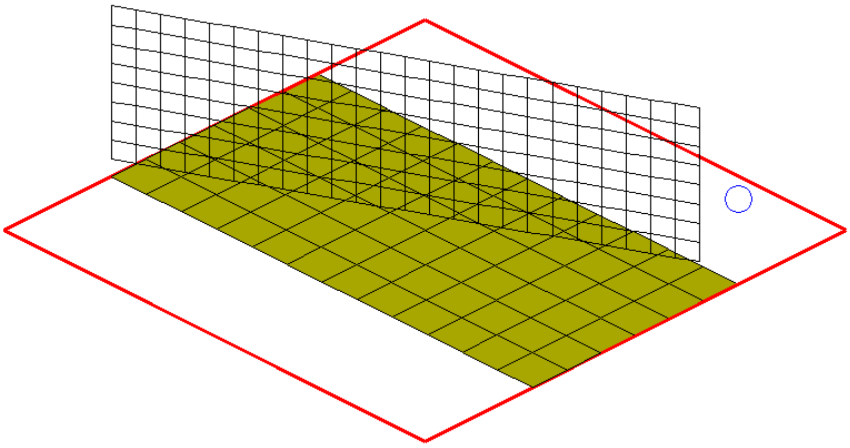

Figure 5: The applied vibro-acoustic model

5 Preliminary conclusions

The detailed data processing is still in progress at the time of preparation of this manuscript. Nevertheless, some preliminary conclusions can already be drawn:

- the supporting structure of the stage is an effective vibration transmitter to relatively large distances
- the stage has clearly defined eigenmodes at low frequencies, but most of these modes lie under the normal operating frequency range of the instruments, used in classical music
- the secondary radiation of the stage, excited by structural excitation of some instruments seems to be there not really dominant
- it seems that the stage surface in the vicinity of airborne sound sources acts as a weak absorber, but also as a secondary radiator at larger distances

As a final conclusion, one can say that the stage most probably colours the sound at very low frequencies, but acts essentially as a sound reflector for the overwhelming part of the operating frequency range of instruments and other sound sources applied on the stage. As a consequence, in cooperation with the structural and architectural designers of the reconstruction, we decided to keep – better speaking, to reconstruct – the stage surface in its original construction, but change the supporting structure to a more slender reinforced concrete beaming, vibration isolated from the wooden stage surface.

The details of the measurement and simulation results will be presented in detail in the course of the oral presentation.

Acknowledgements

The authors of this paper express their sincere gratitude to the acoustical, architectural and structural designers of the reconstruction, especially to Mr Larry Kierkegaard (Kierkegaard Associates, Chicago, USA) and Mrs Éva Arató (Arató Akusztika Kft., Budapest) for the many valuable discussions and advices during the whole period of both investigation and design phase of the works. Special thanks are also due to Mr. Gergely Lakatos, chief technical manager of the project, for his kind cooperation in the preparation of the measurements and for many idea-provoking discussions.