THE ACOUSTICS OF THE HELLENISTIC THEATRE OF EPIDAURUS : THE IMPORTANT ROLE OF THE SEAT ROWS

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1. INTRODUCTION

The Hellenistic theater of Epidaurus, on the Peloponnese in Greece, attracts thousands of visitors every year who are all amazed by the fact that sound coming from the middle of the theater reaches the outer seats, apparently without too much loss of intensity. The theater, renown for its extraordinary acoustics, is one of the best conserved of its kind in the world. It was used for musical and poetical contests and theatrical performances. The presented numerical study reveals that the seat rows of the theater, unexpectedly play an essential role in the acoustics – at least when the theater is not fully filled with spectators. The seats, which constitute a corrugated surface, serve as an acoustic filter that passes sound coming from the stage at the expense of surrounding acoustic noise. Whether a coincidence or not, the theater of Epidaurus was built with optimized shape and dimensions. Understanding and application of corrugated surfaces as filters rather than merely as diffuse scatterers of sound, may become imperative in the future design of modern theaters. *The contents of this paper have been published as Nico F. Declercq, Cindy S. A. Dekeyser, J. Acoust. Soc. Am. 121(4), 2011-2022, 2007. We kindly refer to this paper for more details and for references*

2. BACKGROUND

In the classical world, the 'asclepieion' at Epidaurus was the most celebrated and prosperous healing center; in its vicinity there was the amphitheater, designed by Polycleitus the Younger in the 4th century BC and famous for its beauty and symmetry. The original 34 seat rows were extended in Roman times by another 21 rows. The theater is well preserved because it has been covered for centuries by thick layers of earth. A recent picture of the theater is presented in Fig. 1. Marcus Vitruvius Pollio (first century BC) describes in his famous books 'De Architectura' the state of the art in architecture and shows evidence that man was aware of the physical existence of sound waves. He writes, "Therefore the ancient architects following nature's footsteps, traced the voice as it rose, and carried out the ascent of the theater seats. By the rules of mathematics and the method of music, they sought to make the voices from the stage rise more clearly and sweetly to the spectators' ears. For just as organs which have bronze plates or horn sounding boards are brought to the clear sound of string instruments, so by the arrangement of theaters in accordance with the science of harmony, the ancients increased the power of the voice."

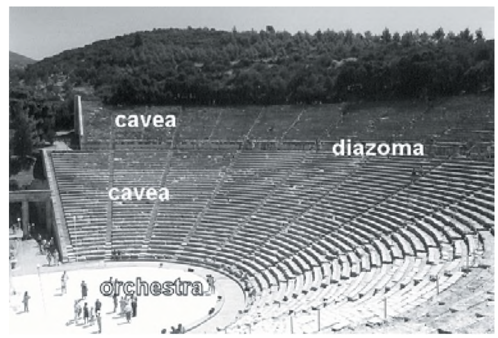

Fig. 1. -picture of the theater of Epidaurus (picture taken by the authors)

This indicates that the construction of theaters was performed according to experimental knowledge and experience and that it was done such as to improve the transmission of sound from the center of the theater (the orchestra) towards the outer seats of the 'cavea'. It has however always been believed, even in the same chapter written by Vitruvius, or the work by Izenour, that it was mainly the aspect of the slope of the theater, as a result of the constructed seats, rather than the seats themselves, that have been a key factor in the resulting acoustic properties. The current study was triggered by the marvels of Epidaurus and by recent advances in the explanation of a variety of diffraction effects on corrugated surfaces. The theory of diffraction of sound is based on the concepts of the Rayleigh decomposition of the reflected and transmitted sound fields. The theory, earlier applied to describe a number of diffraction effects for normal incident ultrasound on corrugated surfaces, has been used successfully to understand the generation of ultrasonic surface waves in the framework of nondestructive testing. The theory was later expanded to include inhomogeneous waves and enabled a description and understanding of the backward displacement of bounded ultrasonic beams obliquely incident on corrugated surfaces, a phenomenon which had been obscure for 3 decades. Even more, it was later exposed that predictions resulting from that theory were in perfect agreement with new experiments. An expansion of the theory to pulsed spherical acoustic waves revealed special acoustic effects at Chichen Itza in Mexico. The advantage of the theory is its ability to make quantitative simulations as they appear in reality. From those simulations, it is then possible to detect and characterize patterns and characteristics of the diffracted sound field such as in the case of a short sound pulse incident on the staircase of the El Castillo pyramid in Chichen Itza. The study indicated that the effects were slightly more complicated than the earlier considered principle of Bragg scattering. In the mean time, the fact that the Quetzal echo at Chichen Itza is influenced by the properties of the sound source as well as the existence of the 'raindrop effect', have been experimentally verified by J. Cruz et al. Bilsen later showed that if one is only interested in the position of time delay lines on a sonogram and not in the entire amplitude pattern, that it is possible to apply a simpler model based on the gliding pitch theory. For a study of acoustic effects at Epidaurus however, we are not interested in the response to a pulse. We are merely interested in how, for each frequency, sound behaves after interaction with the seats of the theater. Therefore the extensive diffraction theory, as used earlier, is the pre-eminent tool. Until now, there have appeared a number of 'explanations' for the excellent acoustics of Epidaurus, such as that sound is driven by the wind because the wind is mostly directed from the orchestra towards the cavea. The wind direction has indeed some influence, but it is also known that the acoustics of Epidaurus is very good when there is no wind or when wind comes from other directions; wind even has a general negative effect because it produces undesirable noise. Another theory is the importance of the rhythm of speech but there are also modern performances taking place at Epidaurus where the typical rhythm of Hellenistic poems and performances composed by Homerus, Aeschylus, Sophocles or Euripides is not there; still the acoustics seems perfect. The last theory is that special masks, worn by performers, may have had a focusing effect on the generated sound, but that does not explain why speakers with weak voices are also heard throughout the theater. Izenour points out that the acoustics is so good because of the clear path between the speaker and the audience. The current proves numerically that the effect of diffraction on the seat rows is probably an even more important effect than the 'clear path effect'.In what follows, we describe the geometry of the theater. Consequently we explain briefly how the numerical simulations are performed. Then we present and explain the numerical results. We end our paper with the most important conclusions. The material parameters at Epidaurus have been taken as: 2000 kg/m^3 for the density of the theater's limestone, and a shear wave velocity of 2300 m/s and longitudinal wave velocity of 4100 m/s. For the air at Epidaurus, we have taken two cases: 'summer', corresponding to an air density of 1.172 kg/m^3 and a (longitudinal) wave velocity of 348.04 m/s; and 'winter', corresponding to an air density of 1.247 kg/m^3 and a (longitudinal) wave velocity of 337.50 m/s

3. CONCLUSIONS

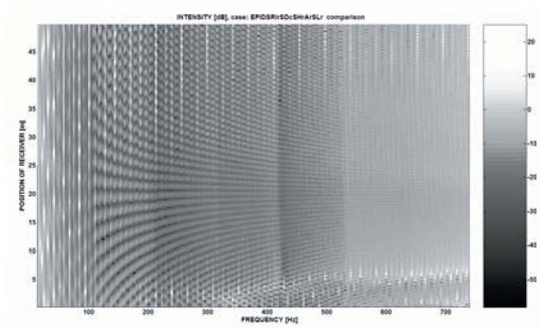

Fig. 2-This figure highlights the effect of diffraction due to the installation of seat rows. At most positions and for most frequencies, the intensity is diminished. However for frequencies beyond 530 Hz, one can see a relatively increased intensity. This is due to the filter effect caused by the seat rows.

It is shown that reflections on the foreground of the theater result in a better distribution of sound throughout the cavea so that all positions become acoustically similar to one another. The installation of seat rows on a smooth cavea generates diffraction effects that change the acoustic properties of the theater. The intensity observed by the audience will be lower than in the case of a smooth cavea. This is not dramatic because the human ear is capable of adapting its sensitivity. More important is that the damping effect is frequency dependent: the seat rows acts like a filter. For frequencies beyond a certain threshold, second order diffracted sound plays an important role and causes sound to be backscattered from the cavea to the audience making the audience to receive sound from the front, but also backscattered sound from behind. This has a positive outcome on the reception of sound. For frequencies below the threshold (mostly noise), the effect of backscattering is less important and is to a great extend filtered out of the observed sound. The threshold frequency of the filtering effect is mainly determined by the periodicity of the seat rows in the cavea of the theater. For Epidaurus this threshold is around 500 Hz, which is usually the upper limit for wind noise. The slope of the cavea does not really influence the frequency values where the amplified frequency band appears and there is no significant difference between the acoustics in summer and the acoustics in winter.

REFERENCES

Nico F. Declercq, Cindy S. A. Dekeyser, "Acoustic diffraction effects at the Hellenistic amphitheater of Epidaurus: seat rows responsible for the marvelous acoustics", J. Acoust. Soc. Am. 121(4), 2011-2022, 2007