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THE ACOUSTICS OF ANTIQUE THEATRES: CANAC'S LIFE WORK REVISITED

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Abstract

In 1967 François Canac published the results of more than 20 years of investigation on the ancient theatres. What he was after was an understanding of the outstanding acoustical qualities of those theatres, which he summed up in two sentences: they can host many spectators, up to 12000 in Syracuse; one hears well from all seats. This outstanding piece of scientific research is however little known in the English speaking world. Our goal is therefore to report on the main finding of Canac, the importance of reflecting surfaces, which he converted into a canonical equation of the antique theatre. We will also report on the techniques Canac used to derive this equation, and conclude, as did Canac in his time, with the acoustical teachings from Antiquity that are still actual.

Keywords

Architectural acoustics, antique theatres, simulation, measurements, acoustical quality.

1. Introduction

François Canac (1886-1969), who began his academic career as collaborator of Marie Curie and Jean Perrin, is best remembered in French Acoustics by his organisation talent [1]. In 1920, he took over the direction of the "Centre d'étude de Toulon" of the French Navy, which he transferred to CNRS in 1941 as "Centre de recherché scientifiques, industrielles, et maritimes" (CRSIM), now "Laboratoire de Mécanique et d'Acoustique" (LMA) in Marseille. He remained director of CRSIM until he retired in 1958. He was co-founder of the journal *Acustica* in 1951.
In 1967, he published his masterly study on the acoustics of the antique theatre [2], which has never been translated into English. The aim of this paper is to present to English-speaking specialists the major findings of F. Canac. This is why the organisation of the paper closely follows the original book, from physical and physiological fundaments to simulation and in situ study.

2. Physical and physiological fundaments

Canac starts his book by reviewing the fundaments of physical acoustics, that is, the attenuation of sound with distance, and its reinforcement by reflections and reverberation. He then moves on to the psychological fundaments of acoustics, which he calls physiological according to a certain French tradition. Most important for him is the Haas effect, which he reduces to the percentage of listeners annoyed by a reflection according to its delay and attenuation with respect to the direct sound (Figure 1).

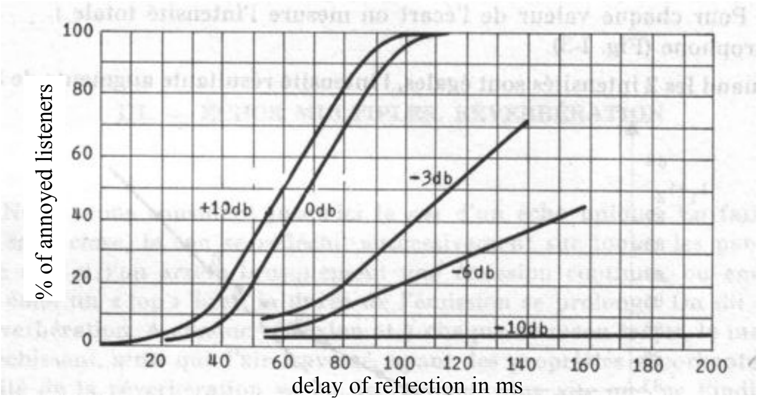

Figure 1 – Haas effect

It is not surprising, then, to notice that reverberation is detrimental for Canac, since it corresponds to reflections that are fully annoying according to Haas. Hence, the main postulate of the book is made clear from the start: antique theatres are superior to modern one since reverberation is greatly reduced.

3. Architectural characteristics of theatres

Canac then proceeds to review the architectual characteristics of the antique theatre. It takes advantage of a plane surface to reinforce sound by reflection, but adds to it the common characteristics of elevating both the orator and the listeners, the first one with a stage, and the second ones on tiers. Further, no roof adds delayed reflections and reverberation to disturb the listeners.
All antique theatres comprise three elements: the tiers (cavea), the orchestra, and the stage. However, there are two basic plans for the antique theatre, as attested by Vitru-

vius [3]: a Greek plan, and a Roman one. Canac goes on with describing the geometrical construction of both types according to Vitruvius (Figure 2), but it has little relevance for acoustics [4]. What is, however, relevant is that the stage is located further away from the tiers in the Greek theatre than in the Roman one, and that the stage of the Roman theatre is enclosed by a high back wall and side constructions.

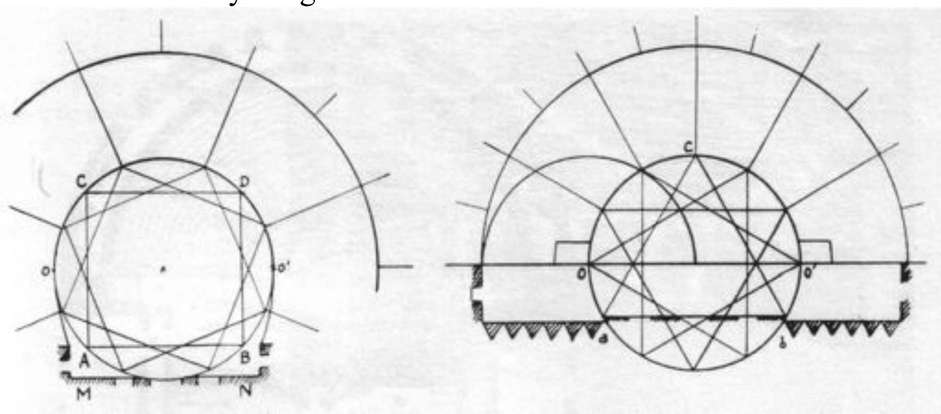

Figure 2 – Ground plan of Greek (left) and Roman (left) theatres

Another characteristic element not seen on Figure 2 is the *diazoma*, an aisle that divided the tiers in two sections of roughly equal sizes. Usually, the slope of the tiers is larger above the diazoma. The characteristics for a theatre are, therefore, its type, the slopes below and above the diazoma, the height and depth of the stage, the width of the stage, and the distance from stage to the front of the tiers.

4. Theoretical analysis of several types of halls of increasing complexity

As said previously, Canac's analysis of the acoustics of the antique theatre basically relies on the analysis of reflections. Therefore, he proceeds steps by step, increasing the complexity of the hall at each step, from a cubic hall to a rectangular one and to a simplified model of the antique theatre: three vertical walls. In each case, he looks for the distribution of image sources and estimates their energetic contribution at the receiver place.

The originality of Canac is to use a modulus, usually the largest dimension of the hall, and compute the arrival times of the contribution of each image source in terms of this modulus. Thus, his analysis reveals that, in a cubic hall with fully reflecting surfaces, the total contribution of the image sources is constant within each time interval corresponding to the modulus, as expected since no absorption is present. When the ceiling and the floor becomes absorbent, the total contribution diminishes drastically as time goes, as expected, and it is interpreted as an acoustical improvement by Canac. The reduction is maximum in the simplified model of the theatre for which only two rows of image sources subsist (Figure 3, where modulus is the shorter dimension).

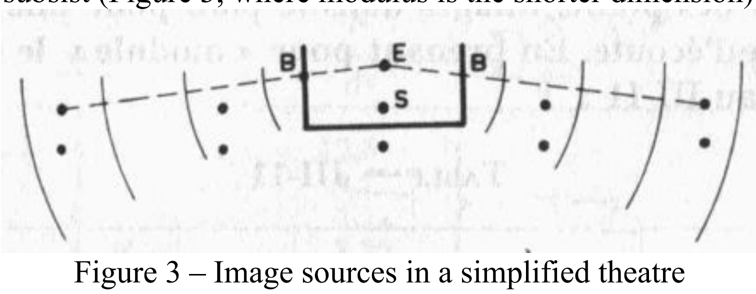

Figure 3 – Image sources in a simplified theatre

In the case of Figure 3, the level during the third time interval is 10 dB down with respect to the first time interval. But one must also look at what happens in a vertical section of the theatre: sound is reflected on the stage and the orchestra plane, depending on the position of the source on stage and of the receiver on the tiers (Figure 4). Basically, for a listener sitting in the median plane (case a), the reflections on stage and orchestra planes are useful only for the remotest seats: stage reflection when the actor stands at the back of the stage; orchestra reflection when he stands in front of the stage.

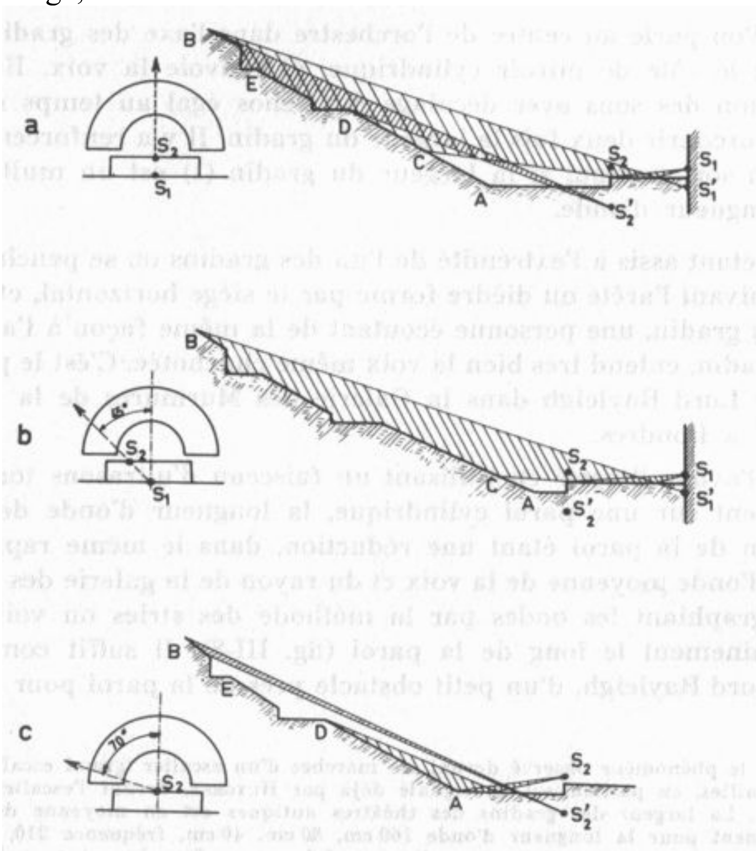

Figure 4 – Reflections on scene and orchestra

At 45°, the situation is different: only the stage reflection is useful, provided that the actor stands at the back of the stage (case b). When he moves to the front, orchestra reflection does not switch on, or only marginally (case c). Acoustical quality decreases in the sides of the tiers.

5. Model study

Canac carried out model studies to study diffraction on the *pulpitum*, or front wall of the stage. In most antique theatres, this pulpitum is ornamented, so that no echo can be heard due to successive reflections on the tiers and the front of the stage. In a similar way, the back wall, when it exists (Roman theatre), is also ornamented.
Canac also used ultrasounds to verify that removing the roof of a hall greatly diminishes reverberation. He then proceeded to study the effect of the stage back wall of the Roman theatre on a 1:100th scale model of Orange theatre. For this later study, Canac designed directional ultrasonic sources, simply by fitting a narrow pipe to a magnetostrictive transducer and adjusting its end position with respect to a cone pointing upward. He also designed directional ultrasonic receivers of similar construction, except that the end

of the pipe was fitted with a mirror orientated toward the centre of the theatre. Since the receiver was mounted on an arm rotating around the centre of the theatre, all positions along any row of the tiers could be measured.
Figure 5 presents the sound intensity measured along a row located in the upper part of the tier of Orange theatre, displayed as polar plots with angular positions corresponding to the different seats. It successively presents the case where the back wall is flat, the case without a back wall, and the case with a model of Orange back wall. Without any doubt, adding a back wall increases the intensity at all seats along the row, and making it diffuse as in Orange increases homogeneity.

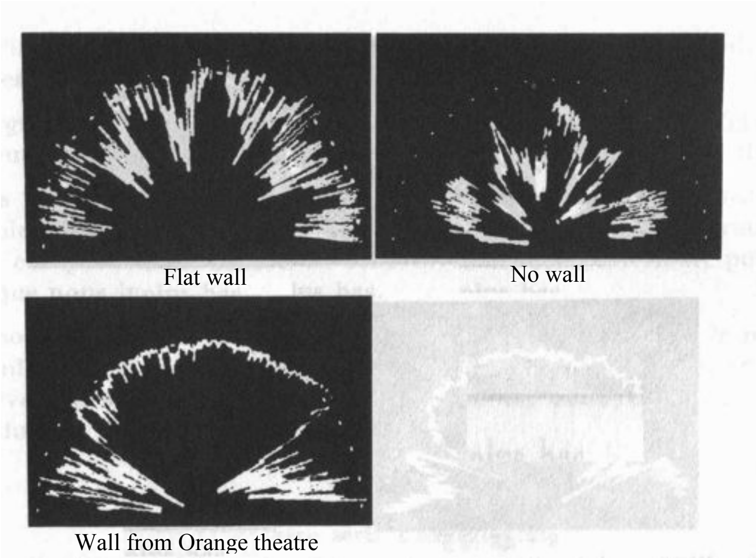

Figure 5 – Effect of diffusion on stage back wall

6. Canonical equation of the antique theatre

Having developed all the concepts he needs, Canac can now derive his canonical equation of the antique theatre. In fact, this equation simply expresses the listening angle (ε in Figure 6) as a function of the theatre dimensions, and is therefore different in different theatres. The basic idea behind this equation is that the listening angle must be large enough – at least 5° as in Epidaurus, but best 17° as in Aspendos – so that no image source is masked by the spectators sitting in the rows in front. Thus, the listening angle is an indicator of the acoustical quality of a theatre.

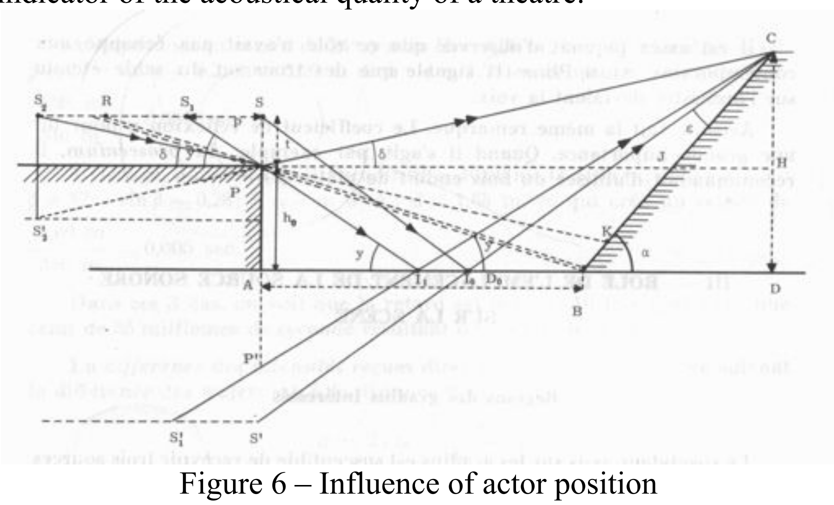

Figure 6 – Influence of actor position

It can be seen on Figure 6 that the listening angle always correspond to the image source obtained by reflection on the orchestra plane. And since this image source moves upward when the stage height is decreased, the listening angle is increased when the stage is lower. Hence, for acoustical quality, a low stage his preferred.
Figure 6 further shows that the listening angle is also function of the position of the actor on stage. More precisely, the actor must stands in the front of the stage, between positions *S* and *R*, to take advantage of the reflection on the orchestra plane. On the other hand, reflection on the stage only occurs if the source is located beyond position S_2, always located behind *R*. At S_2, only the top row of the tiers takes advantage of the stage reflection, but more and more rows are concerned as the source moves further back.
As a consequence, Canac concludes that the stage must be narrow, with a depth of 4 to 5 m, which precisely is the case in Greek theatres. Some later Roman theatres have deeper stages, but they are deep enough so that stage reflection occurs.
From this reflection analysis, Canacs moves on to compute the sound intensity and its relative variation throughout the tiers.

7. *In situ* study of acoustical quality

The last chapter of Canac's book is devoted to the *in situ* analysis of the acoustical quality of some theatres, an activity which occupied most of his leisure in the 20 years preceding the publication of his book. This analysis is based on two methods: measuring the distribution of sound intensity in the theatres; and assessing intelligibility using logatomes. He points out that Vitruvius explicitly advised the use of monosyllabic words (*sol, lux, nos, flos*) to evaluate the acoustical quality of a theatre. He also measured arrival times of echoes, and for this purpose he developed specific clappers that could produce wide band impulses.
Then Canac moves on to a typology of the antique theatres in 4 classes: Greek theatres, with a circular orchestra; Roman theatres, with a semi-circular orchestra that can be prolonged in a horseshoe; Greek theatres modified in Roman times – also called mixed theatres – where both structures can be seen, allowing useful quality comparisons; and odeons, always smaller and with special architectural characteristics for music.
For all classes of his typology, Canac reports measurement made in a few representative example of the class. Figure 7 present the distribution of intelligibility (in percents, numbers inside square) and of levels in dB for both 750Hz and 1kHz in a mixed theatre: Dyonisos in Athens. The Roman stage, closer to the tiers, increases the levels in the first rows, whereas the Greek stage increases intelligibility. At larger distances, the difference tends to vanish.

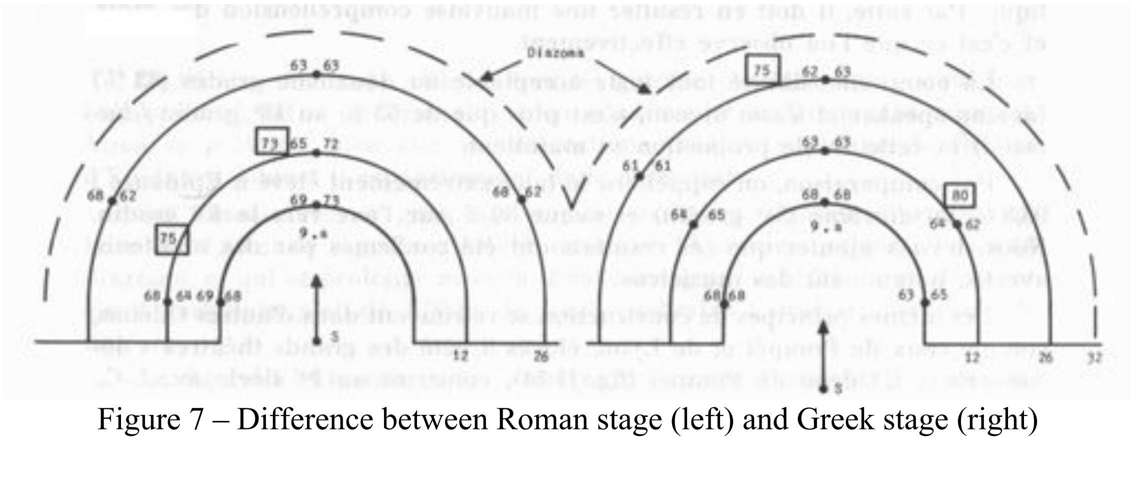

Figure 7 – Difference between Roman stage (left) and Greek stage (right)

When possible, he compares intensity measurements with computation using the reflection pattern: results agree, confirming the analysis of Section 6. Thus, the antique theatre is an acoustical amplifier located around the source.

By comparing similar theatres with and without back wall, Canac was also able to confirm that the back wall decreases intelligibility, though it remains high. In a similar way, adding a wooden floor on the stage increases intelligibility, especially in the upper rows where the reflection on stage is most useful (Section 6)

8. Conclusion

The masterly analysis reported in his book confirms, of course, Canac's initial postulate that roofs are detrimental for acoustical quality. But another conclusion is the advantage of reflection on the back wall if the stage is shallow, pleading for shallow stages in opposition to current theatre practice. Canac further advises to make the lower part of the back wall flat, so as to reinforce the voice of the actor, but it must be diffusing or absorbing in its higher part so as to prevent late echoes due to successive reflections on the tiers and back wall. For similar reasons, he advises to make absorbent the sidewalls of the stage. Last but not least, the slope of the tiers is an essential characteristic of antique theatres.

From this, Canac moves to recommendations that can be summed up as: do not hinder direct sound; add early reflections; suppress late reflections and reverberation. He also strongly advises to differentiate theatres for speech from concert halls.

Canac's analysis solely relies on the distribution of reflections. For doing so, he makes use of a technique that was to become the standard in room acoustics: ray tracing, and the determination of image sources. However, his use of the technique is embryonic, and reduced to the first reflections. No computers were available at the time of Canac to compute the full distribution of reflections, and this may explains the main postulate of Canac: the negative effect of reverberation for acoustical quality. This is why, in his eyes, antique theatres, especially Greek ones, are superior to modern ones.

In the years following the publication of Canac's book, the irruption of computers in Acoustics completely changed the approach: the first modern paper on ray tracing was published only one year later by Asbjørn Krokstad and his collaborators [5].

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