Theatres from roman age to renaissance: a short survey on the meaning of reverberation time measurements

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In the mind of C.W. Sabine, reverberation time was thought as a numerical index of what was happening in a closed hall when a sound source acting within was suddenly stopped: the original idea was that sound rays where travelling in any direction reinforcing residual sound energy, but at the same time overlapping audible messages that these rays where carrying to the listener's brain.
As well known, he stated a formula linking the R.T. value to the hall volume and to the capacity of the impinged surfaces to keep a fraction of the sound energy: from one hundred years to now, many authors researched in the field and stated the best R.T. values for the listener of different kinds of sound.
Surely Greeks and Romans did not know the possible existence of such a parameter, as they acted in open spaces, neither Vitruvius and, successively Alberti, Milizia, Poletti and so on, even if the tile cover utilized by the Romans to preserve from sun light and rain was avoiding that some sound energy dispersed in the sky.
Surely the modern computer assisted measurement techniques are able to keep some kind of sound decay even in an ancient theatre, but we are aware, as Greeks were, that they are derived only from reflections travelling quite horizontally, between vertical structures, or inclined between actors and spectators via orchestra floor, when not occupied from public.
This paper will present a specific and synthetic survey on the subject.
Keywords: acoustical parameters, reverberation time, running strength

Sui teatri dai Romani al rinascimento Italiano: una breve rassegna circoscritta al significato della misura del tempo di riverberazione
Sabine concepì per la prima volta nella storia una tecnica di misurazione di quanto accade quando in un ambiente chiuso la sorgente sonora improvvisamente tace: l'idea originale fu che i raggi sonori emessi in precedenza dalla sorgente contuassero il loro cammino rimbalzando sulle pareti come tante palle, lasciando di volta in volta sulle stesse parte dell'energia sonora da loro veicolata; l'ascoltatore veniva quindi immerso in un campo sonoro degradante più o meno regolarmente fino a raggiungere il silenzio, successivamente meglio definito nel classico degrado di 60 dB. Nei tempi successivi altri Autori hanno determinato quali dovevano essere le caratteristiche di uniformità di questo campo ed il suo valore di degrado ottimali per ascoltare e gradire diverse tipologie di campo sonoro.
Sicuramente Greci e Romani non conoscevano la possibile esistenza di questo paramentro, tanto più che i loro teatri sorgevano all'aperto, condizione chiaramente antitetica all'uniformità del campo sonoro: né Vitruvio né, tanto per ricordare qualcuno, i suoi successori Alberti, Milizia, Poletti ed altri invocano il tempo di riverberazione, ben diverso dal semplice riverbero.
Sicuramente le tecniche di misura supportate dai moderni programmi di calcolo consentono oggi di valutare sia il valore (o ì valori) del Tempo di riverberazione più idoneo a caratterizzare le diverse fasi del decadimento del campo sonoro anche in uno spazio aperto, ma siamo tutti ben consci (come del resto Greci e Romani) del fatto che i diversi picchi che compaiono lungo le curve di decadimento sono imputabili solo a riflessioni da strutture verticali collocate sul piano più o meno orizzontale della scena, dell'orchestra e della cavea.
Questa sintetica quanto accurata ricostruzione desidera appunto presentare questo quadro.
Parole chiave: tempo di riverberazione, forza del campo sonoro

1 | Introduction

First of all, it seems necessary to take this opportunity to recapitulate some relevant elements in the history both of architecture and acoustical science development.

In a previous paper [1], some particular aspects emerging from the examination of major findings in the field were explored:

- existence of a hill were to lean some kind of tiers useful for spectators, to enhance seeing and listening capabi-

lity, with the consequent research of an optimal shape, from the original rectangular one to the final choice of the circular one;
- location, to promote the acoustical aspect going away from any other possible source of noise (typical example: Epidaurus location) and other doubtful choices for taking advance from local air flows (exposure to sea, sun path);
- resonators, introduced by Vitruvius [2], but not so widely diffused in the field.

Not to be excluded, other factors may locally emerge from specifical researches like for instance [3] where the nature of the material utilized was investigated, or [4] where a specifical study was devoted to spectators and their dressings [5]; finally, the use of masques contributed to reinforce direct sound.

It seems also relevant to fit the problem into the historical frame of acoustical knowledges at the time when ancient theatres were built.

In the last fifty years electronic instrumentation allowed us not only to memorize the impulse response received from a microphone but also to elaborate it quite in any possible way.

The first step of this "new age" was the automatic calculation of the reverberation time and this event signified the disappearance of protractor rule from our desk, soon after the availability of a reverberation time calculated on any possible temporary base, such as EDT, T20, T30, and so on.

A new step was to compare the amounts of energy received in different time intervals, so to have the various clarity indexes, like C50, C80, and so on.

A particular index was derived from the comparison of the really received sound level in a selected position to that hypothetically receivable from the same omnidirectional source in an open field ten meters far, the strength G.

All these indexes are now well known to quite everybody involved in acoustical measurements in general and particularly within spaces devoted to theatrical performances and are really of strong interest for those involved in planning modern spaces like multipurpose auditoria or reuse of any other, like churches, sport arenas and, why not, Greeks and roman theatres even if open spaces.

They are of fundamental relevance also for those involved in restoration of ancient Opera Houses [6] so to save their original state, like for instance in rebuilding "La Fenice" theatre in Venice [7], or restoring "La Scala" theatre in Milan [8].

In the last century many researchers involved in the history of ancient theatres utilized the modern acoustical parameters trying to evaluate the acoustical ability of architects working in the past, from Greeks to the modern age, but in my really not short career I never found anyone of them speaking about parameters that didn't exist at their times!

At the most, someone speaks of "reverberation" or "reverberance" but not of "reverberation time", till the coming on the scene of W.C. Sabine [9].

Even the availability of modern techniques to realize either physical or virtual models, more and more realistic, are responsible of any researcher's removal far from the reality; so, my impression is that the more reliable study on open air theatres will remain that developed in [10] utilizing geometrical methods.

2 | State of art

It is possible to think that god-fearing is strictly linked with the man existence: so, even the need to involve others in our religious thoughts is originally linked with our existence and for theatrical expression may be the same.

We have proof of this when Egyptians began to leave some paper, at the time of the XVIII dynasty [11].

Looking to the archaeological remains, it seems possible to locate the beginning of the theatres building art in the VI century b.C. [see f.i. 12], with the transition in some century from the original squared shape (to promote a better use of the field) to the best known semi-circular one [12, 13] (nearer to the shape of direct sound waves).

Following the word of [14], we know that "Greeks of the Pythagorean school were primarily concerned with the science of musical intervals, the branch of musicology sometimes referred to in ancient writings as *canonics* or *harmonics*.

The musical consonances described as the octave, the fifth and the fourth were almost certainly known long before Pythagoras, but the success he had in identifying these consonances with the ratios of simple whole numbers was not only a mayor advance in the theory of music, but also a source of encouragement and support for the numerological slant of Pythagorean doctrine. In the early experiments ascribed to Pythagoras, the auditory judgement of consonance was used as a criterion to establish the corresponding numerical ratios. In due course, however, Pythagoras and his followers lost faith in the evidence of the senses as a criterion of judgement and sought to interpret all phenomena as manifestation of mathematics".

"Anaxagoras (c.a. 499-428 b.C.) explained it explicitly by seeing that trough the weakness of science-perceptions we cannot judge truth".

Some time later, "Aristotle (384-325 b.C.) gave the most articulate explanation of the extravagant notion", asserting the untruth of these ideas of Pythagorean school.

The most enduring, not unique, contribution by Pythagoras was the inverse proportionality between pitch and length of a vibrating string; furthermore, there was the claimed experiment about the pitch emitted from two different hammers, having the weight one the double of the other, hitting on an anvil. Boethius (a.D. 480-524), one of the best Aristotle's translators, refers that Pythagoras invented the monochord to test relations existing between pitch and length of a vibrating string.

The mathematician Archytas (428-360 b.C.) stated that "sound is impossible unless there occurs a striking of objects against one another" and it concluded his argument with a summary claim "that hight notes are in swift motion, low tones in slow motion, has become to us from many experiments".

The idea that the speed of sound was linked to its frequency was not completely drove away even in Aristotle time, but Theophrastus of Eresus (372-288 b.C.), Aristotle's successor in the guide of the peripatetic school, finally observed that two different, concord sounds would maintain always in this condition all along their common path, so it was evident that the speed was the same for both.

Aristoxenus [15], a philosopher and musician who lived in the III century b.C., was involved in the discussion about musical scales and was aware of many aspects of the generation and overlapping of sounds, first of all the propagation spherical rule. So, they probably found only on the field that some vertical surface or structure could generate reflected sound reinforcing the direct sound: for instance, the particular diffraction effect in the Hellenistic amphitheatre of Epidaurus generated by the nature of stone utilized for the seats was unexpected [3].

Even the great geometer Euclid of Alexandria (330-275 b.C) was involved in the question about musical intervals but didn't add anything to the work of Aristotle and his followers, even if his theory of simple numbers was the best presented.

The first paper we found on the subject is the famous treatise by Vitruvius [2] where, it is well known, we can find many notes and geometrical details about the shape of a theatre either Greek or Latin, but quite nothing about natural reverberance: only some words are devoted to sound reflection, more is devoted to artificial reverberance dealing with sounding vessels.

The first appearance of natural reverberance derived by chance from the introduction of some kind of cover as sun or rain protection.

After a long period of silence about the buildings devoted to theatrical performances, in XVII-XVIII century the interest on these covered spaces raised, so we can find in Italian literature some writing speaking of them, like for instance Carini Motta [16]; in Europe Pierre Patte [17] was the first to announce in his book cover that his studies were placed upon "les principle de l'optique et de l'acoustique".

In particular, the declaration of Patte clearly confirms that, at least till the end of XVIII century, acoustical reasons were not the first problem for everyone involved in theatrical design.

Among the Italian architects involved in design of theatrical space during the XVIII century exploded deep research about the best shape for the audience, but even in this case we found only visual reasons; maybe there were also some acoustical reasons that each designer kept for himself or his family, like in the case of Galli da Bibiena. We have the same impression reading [18] were the work of less famous architects who signed many projects in Italy, like Aleotti and Poletti, is taken into consideration.

In Europe, the situation is well represented, in my opinion, from the words of the famous architect C. Garnier at the opening of his Opéra in Paris, who declared that he afforded the big problem of the acoustical result like an acrobat launching himself in circus arena without any safety net [19].

A very interesting book was written by F. Canac [10] in 1967, who put in clear evidence the very unique importance, in an ancient theatre's acoustic performances, of reflections coming from the orchestra surface in the construction of some reflected and reinforcing sound.

So, when W.C. Sabine [9] was charged to modify the agreeability of sound reception in the famous auditorium of Fogg Art Museum, nobody else was able to measure what he called "reverberation time" and to link it to the sound absorption power of materials facing the sound source. It is of fundamental relevance that Sabine was acting within a closed space, in particular claiming for an uniform acoustical field, that is, euphemistically to say, far away to what happens in an **open space**!

3 | ERATO project

In the frame of the ERATO European project, many researchers were involved both in measurements and simulations in Greek and Roman theatres: three annual reports were published where in particular we can find the achieved results. At the end, a symposium was held in Istanbul [4].

An unexpected result was the amount of RT, as stated also in [20]: RT was higher than expected while SPL was almost that of free field.

Maybe, it would be interesting to study the slope of the impulse response, that only some new instrument shows, while usually they give directly the numerical result evaluated on the base of a time interval selected from the same software: in these cases EDT, T20 or T30, parameters that practically take into consideration only the direct sound and some first reflections.

Rindel, who acted as Coordinator of ERATO research, firstly analysed in [21] some result achieved, then studied in deep in [22] where in particular he reproduces some decay curve denoting clearly the presence of many concentrated responses, better ascribable to eco than reverberated sounds (in Sabinian sense); finally in a contribution to the recent symposium in Verona [23] the results achieved bring to the conclusion that "EDT is not a usable parameter" and that T20 "is highly unreliable", instead G … could be a usable parameter for open-air theatres".

At that point it seems relevant to debate on the meaning of the parameter G, originally proposed to quantify the amount of acoustical energy apported from the envelope to direct sound, usually relating the SPL measured in some position in a closed hall while an omnidirectional source is acting, and that theoretically achievable whit the same source in a free field ten meters far from the same source.

In the case of an open space, like a Greek theatre, it seems more realistic to compare the measured value with the result achievable in the same place in a flat and free field (always with the same omnidirectional source).

This new version of G was firstly suggested in [20], then presented in clear from the Author and others [24] as G_{re}, relative strength:

$$G_{re} = 10log_{10}\left[\int_0^T p^2\,(t,x)dt / \int_0^T p_{ff}^2(t,x)dt\right] \quad (1)$$

where ***p*** represents the sound pressure value measured in place and $\boldsymbol{p_{ff}}$ the theoretical value generated in an equivalent flat and free field **at the same distance** from an omnidirectional source: this definition seems quite the same as now presented in [23].

4 | Concluding remarks

Reading the papers of Sabine [9], it is evident that it is out of discussion the possibility to apply his work to an open field, even if we have reflections. In the field fancied, the decay slope must be rather regular during the canonical 60 decibels. Nevertheless, it is possible to limit this time interval to put in evidence some particular effect like direct sound, early sound and so on [25].

When carrying out reverberation time measurements it is always recommended to catch as first element the full slope of the decay, from which it is possible to deduce many useful informations about the acoustic field generated from the impulse response.

Chiefly in the case of ancient Greeks and Roman theatres, it seems more realistic to examine the strength of sound G better related to a real position in the field than to a fixed distance from the source.

Considerazioni conclusive

Leggendo gli scritti di Sabine [9], appare fuori discussione la possibilità di utilizzare il suo Tempo di riverberazione quale strumento per valutare la qualità Acustica di uno spazio aperto, anche in presenza di componenti riflesse: il risultato dei suoi esperimenti è applicabile solo a campi con decadimento sonoro più o meno regolare. Ciò non toglie che limitando il tempo di ascolto del decadimento possano derivarne aspetti particolari, quali la o le componenti dirette e le prime component riflesse [25].

In genere, eseguendo misure del tempo di riverberazione, in genere è sempre raccomandato di registrare la curva del decadimento del livello sonoro, sempre foriera di utili informazioni.

Appare invece di grande interesse la forza G_{re} (E in [23]) relativa alla posizione reale sul campo anziché quella classica riferita alla misura standard di 10 m dalla sorgente, specie nel caso di teatri Greci e Romani.

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