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MEASUREMENT OF REVERBERATION TIME USING TIME DELAY SPECTROMETRY (TDS)

G. PAPANIKOLAOU, V. PSAROUDAKIS and M. NISTIKAKIS

Department of Electrical Engineering
University of Thessaloniki, Greece

1. Introduction

In a series of papers printed in the Journal of Audio Engineering Society in late sixties and early seventies, Richard C. Heyser introduced a revolutionary measurement technique which he named Time Delay Spectrometry (TDS) [1–6]. This technique allowed measurements to be conducted on systems that are inherently time-delaying, such as acoustic and electroacoustic systems, even non-linear ones, and being difficult to be measured by means of traditional techniques, due to the time delay involved in the measurements.

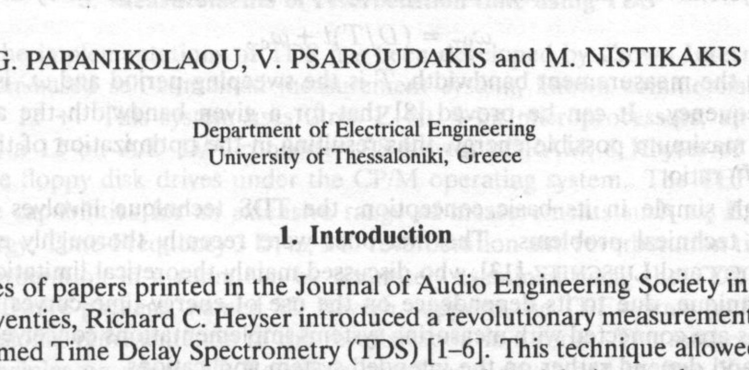

FIG. 1. Simplified block diagram of a TDS measuring system.

In Fig. 1, the simplified block diagram is shown of a system capable of performing measurements using TDS. The frequency converter is heterodynously connected to an oscillator which produces the intermediate frequency f_{if} of the analyzer. The difference signal is shifted in frequency into the acoustic region by the converter and produces a control signal that is fed to the system under test. The spectrum analyzer receives the microphone output and displays it on the vertical axis of a CRT display; while on the horizontal axis, it represents the corresponding frequency of the control signal.

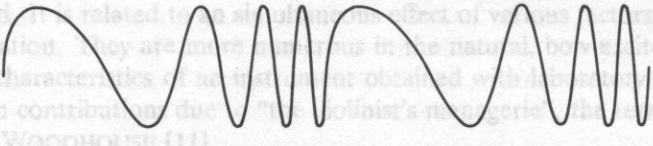

FIG. 2. Periodic swept tone used as a test signal in TDS

Figure 2 shows the periodic swept tone that is used as a control signal by the measurement system. The instantaneous frequency of such a signal is given by the expression

$$\omega_{0T} = (D/T)t + \omega_c ,$$

where D is the measurement bandwidth, T is the sweeping period and ω_c is the carrier angular frequency. It can be proved [8] that for a given bandwidth the above signal carries the maximum possible energy, thus resulting in the optimization of the signal-to-noise (S/N) ratio.

Although simple in its basic conception, the TDS technique involves many theoretical and technical problems. The first ones were recently thoroughly examined by VANDERKOOY and LIPSCHITZ [13], who discussed mainly theoretical limitations inherent in that technique, due to its dependence on the use of energy-time curves (ETC). The second ones are connected with measuring systems implementations conceived by various producers and depend rather on the intended system applications.

While theoretical approach to the TDS technique is widely known due to the above mentioned papers, and, first of all, to the anthology of Heyser's works [9], as well as to other recent publications devoted to those problems [10], [11], many practical questions concerning applications of the TDS techniques remain unexplained, which impedes or delays a broader use of TDS systems. The present authors, basing on their experience collected during TDS system applications, especially to reverberation measurements, present below a practical approach, facilitating the appropriate use of TDS measuring systems in various applications.

2. Reverberation time measurements

The reverberation time of a room is defined as the time required, from the moment the sound source ceases to emit for the sound level to decay by 60 dB, or to the 1/1000 of the original sound pressure value. The reverberation time is a basic characteristics of a room and is widely used to determine its acoustic properties. The above definition is related to the characteristic listening properties of the human ear, since it represents an attenuation from a normal listening level down to the threshold of audibility. As the differential sensitivity of hearing organ to sound intensity, described by the so-called Weber-Fechner formula, has a logarithmic character, i.e. linear versus a logarithmic intensity scale, so an objective measurement of the decaying sound, adequately representing the subjective sensation of reverberation time, may be sufficiently limited to a two-point approximation of the decay, i.e. to the direct measurement of time elapsed between two prescribed levels of the decaying sound. Such technique of reverberation measurement was intuitively introduced by W. C. Sabine, pioneer acoustician at Harvard University. His measurements led him to establish his empirical formula, showing dependence of the reverberation time on room parameters: volume and absorption; theoretical explanations came later to.

Many improvements have been introduced since Sabine's works into reverberation measurement technique. Reviewing them now would be time consuming and irrelevant in this context. A general tendency to improve the accuracy of measurements may be, however, concluded. The last improvement of these techniques is described in the following sections.

3. Measurements of reverberation time using TDS

One of the implementations of TDS has been developed by Crown International. It is a computer-based self-contained measurement system, known commercially as TEF 12 and TEF 12 +. This system uses three Z–80, 8–bit microprocessors, an arithmetic coprocessor, a 12–bit A/D–D/A converter, 98 Kbytes of RAM, 6 Kbytes of ROM and two 1–Mbyte floppy disk drives under the CP/M operating system. The TEF 12 system provides the capabilities for an extensive range of measurements such as, Energy-Time (ETC), Energy, Time-Frequency 3 D, ..., 3 D reverberation and reverberation time RT–60.

The reverberation in a room can be accurately examined using the TDS technique. A special software package, named 3D Reverb, supports the TEF system and allows the three-dimensional representation of the reverberation in a room. The mathematical and acoustic principles on which 3D Reverb is based were developed by Ben Kok of Peutz and Associates in Holland as a support package for the basic TEF programme [8].

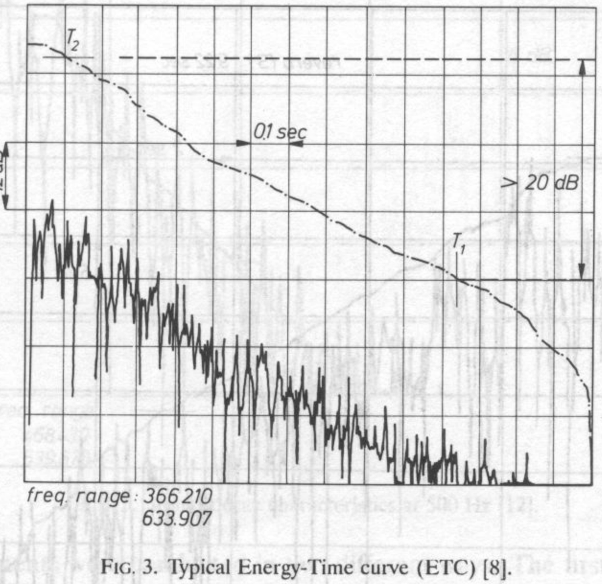

FIG. 3. Typical Energy-Time curve (ETC) [8].
Schroeder 1027288 usec; 1160.8260 Feet; -41.66 dB; dif. -38.79 dB; Sweep Rate 20 Hz/s JOB 00;
Time Spar 0 usec, 1490489 usec; Dif. Spar 0.000E+00,1.684E+03 Feet.

At the beginning of the measurements we will have to set the starting time T_2 and the ending time T_1. This is done using the ETC curve (Fig. 3) [8], so that the dynamic range of the data between T_2 and T_1 exceeds 20 dB. Moreover, proper setting of the sweeping rate S, the initial frequency F_1 and the final frequency F_2 must be made depending on the measured room. Thus, we have two categories of rooms: "small" and "large" ones. The second category includes churches, theatres and concert halls with a seating capacity of more than 1000.

The reverberation time of a room is measured using the existing sound system of the room or using a separate source placed at the speaker's position. The microphone is placed at a predetermined point and the measurements are repeated in various places, in order to minimize the possibility of an unwanted physical parameter affecting the calculations. Finally, it should be stated that this technique relies on the statistical sampling of a number of measurement points. The accuracy of the measurement can be improved by increasing the number of those points but at the cost of a longer time required to complete the measurement.

In Sec. 4 we examine the use of TDS in evaluating the reverberation characteristics of a domed stadium whereas in Sec. 5 we describe similar measurements made inside a theatre hall. In both cases the results obtained by TDS are compared to those yielded by traditional techniques.

4. Reverberation time measurements in a domed stadium

As a first example of reverberation time measurements using TDS, we consider a study by David E. Marsh, Jack E. Radoff and Ashton Taylor conducted on Harris County

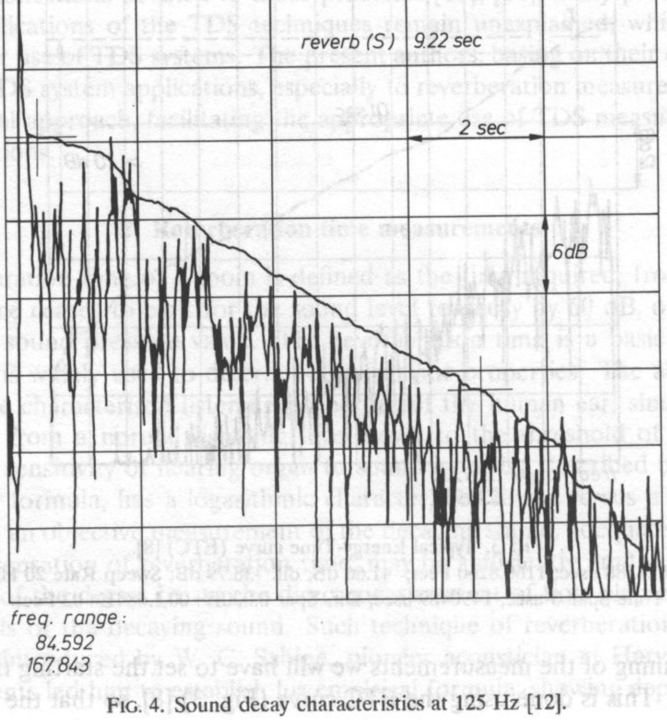

FIG. 4. Sound decay characteristics at 125 Hz [12].

Domed Stadium, Houston, known around the world as Astrodome [12]. Astrodome has a total volume of more than 13×10^6 m^3 and a seating capacity often exceeding 40000.

Table 1. Reverberation times obtained from ETC measurements made on various seating levels [12]

FREQUENCY	31.5	63	125	250	500	1*k*	2*k*	4*k*	8*k*
MEZZANINE LEVEL-AISLE 461, ROW C, SEAT 2									
RT-60	9.09	18.71	9.22	6.49	4.56	4.92	4.30	4.50	0.62
LOGE-AISLE 672, ROW A, SEAT 3									
RT-60	10.82	14.02	8.21	7.12	6.67	6.28	5.60	3.99	0.93
RAINBOW LEVEL-AISLE 757D, ROW 7, SEAT 10									
RT-60	14.36	19.12	9.28	6.30	5.71	5.70	4.00	4.95	0.99
FIELD LEVEL-AISLE 267, ROW P, SEAT 1									
RT-60	11.03	20.73	10.26	6.93	5.48	5.99	4.62	4.04	*N/A*
FIELD LEVEL-CENTER OF FIELD									
RT-60	14.67	21.93	12.25	6.86	5.44	4.98	*N/A*	*N/A*	*N/A*
AVERAGE REVERB TIMES									
	11.99	18.90	9.84	6.74	5.57	5.57	4.63	4.37	0.85

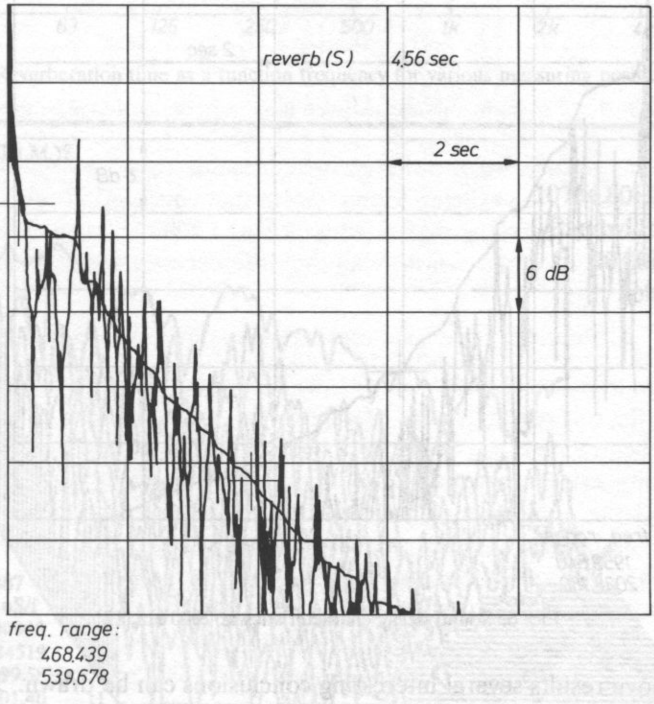

FIG. 5. Sound decay characteristics at 500 Hz [12].

The measurements were conducted in two different ways. The first was based on the TDS technique, while the second — on the traditional measurement of the reverberation time. According to the first method, the TEF system produces a control signal that drives the existing sound system of the room and measurements are taken at various positions. For the traditional measurement of reverberation time, a small cannon was used in order to produce the high sound pressure level required to disturb adequately the huge volume noise levels encountered during the measurements. Most of the measurements were made in the octave bands ranging from 63 Hz to 4000 Hz. The cannon blasts were recorded and subsequently analyzed in a laboratory.

Figures 4 through 6 illustrate the typical sound decay characteristics produced by the existing sound system in the frequency range from 125 Hz to 2000 Hz. Table 1 shows the values of the reverberation time obtained from ETC measurements at various listening positions, whereas Fig. 7 gives a graphical representation of the reverberation time as a function of frequency. In Fig. 8 we have a three-dimensional representation of the reverberation time as measured at points in the mezzanine seating areas. Figure 9 shows a comparison between the reverberation time measured using the TDS technique and the time obtained from the traditional measurements.

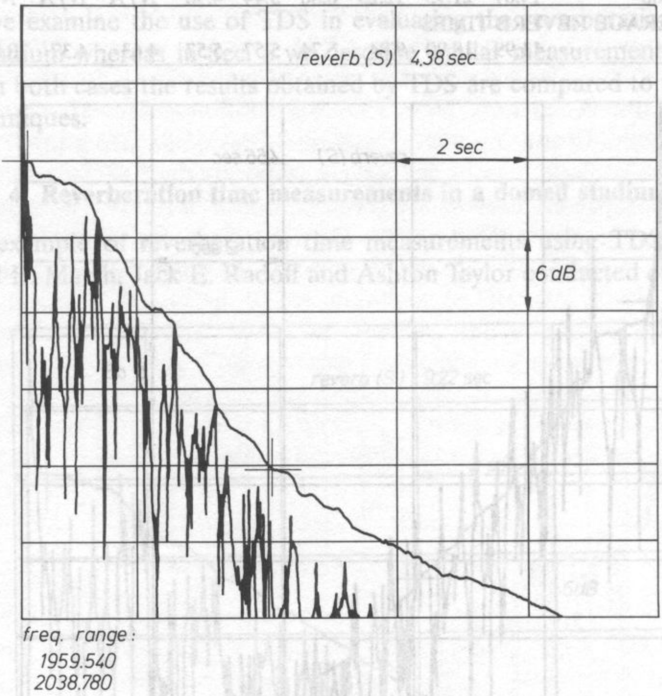

FIG. 6. Sound decay characteristics at 2000 Hz [12].

From the above results several interesting conclusions can be drawn. The ETC curves represent the energy of discrete sounds arriving at a point as a function of frequency. From these curves it can be seen that the reverberant sound field does not appear immediately but some 500 ms after the arrival of the direct sound at the listening position. Table 1 shows that the reverberation time is nearly independent of measurement position at frequencies between 250 Hz and 8000 Hz. Below 250 Hz, the dependence is more pronounced but the curves for various measuring points are essentially the same (Fig. 7). Moreover, the reverberation time at 63 Hz appears to be considerably longer that at other frequencies including that of the 31.5 Hz, which probably is due to particular resonant conditions.

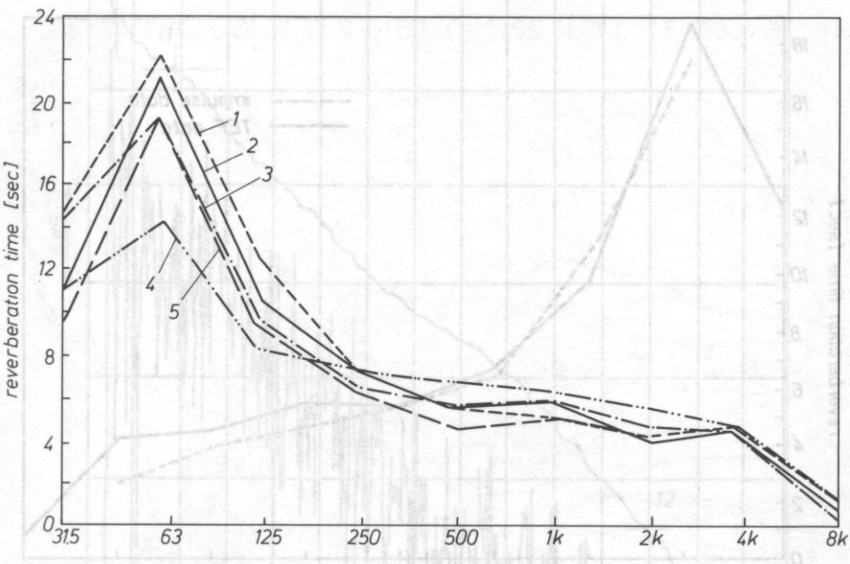

FIG. 7. Reverberation time as a function frequency for various measuring positions [12].

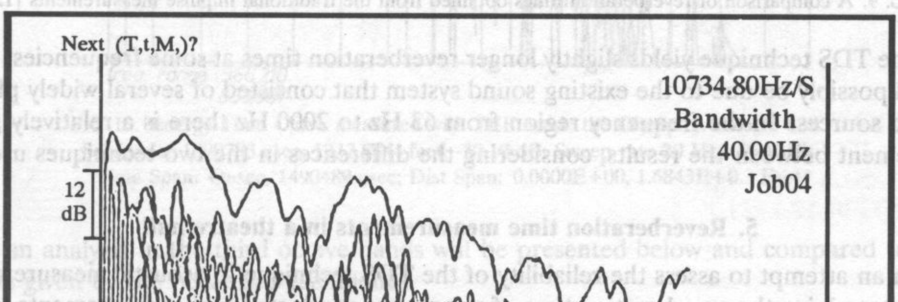

FIG. 8. Three-dimensional sound decay characteristics as obtained from measurements on the mezzanine level [12].

Figure 8 shows that the sound decay is faster at high frequencies than at midrange and low frequencies due to the increased air absorption. Finally, it is interesting to compare the two techniques used for the measurements (Fig. 9). The curves have the same shape

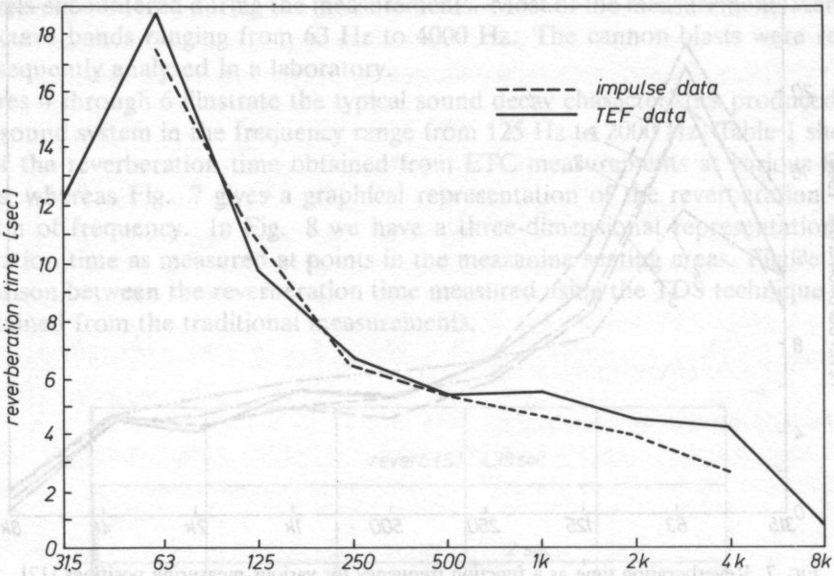

FIG. 9. A comparison of reverberation times obtained from the traditional impulse measurements [12].

but the TDS technique yields slightly longer reverberation times at some frequencies. This could possibly be due to the existing sound system that consisted of several widely placed sound sources. In the frequency region from 63 Hz to 2000 Hz there is a relatively good agreement between the results, considering the differences in the two techniques used.

5. Reverberation time measurements in a theatre hall

In an attempt to assess the reliability of the TDS technique in acoustic measurements for determining the reverberation time of a room, we conducted such measurements inside the Olympion theatre hall in Thessaloniki with a seating capacity of about 1000. This hall suffered from serious acoustic problems such as strong delayed reflections and poor intelligibility and the purpose of the measurements, to be described, was to investigate those problems and come up with the possible solutions. The sound source for the measurement was a loudspeaker placed at the middle of the stage front, and the measuring microphone was placed at the middle of the fifth row of seats, and at a height slightly above the head of an average seated listener. The reverberation time was then calculated using three different techniques. Same microphone positions were employed for each of them.

The first was based on TDS and the use of the 3 D Reverb software package, as described in Sec. 3. Figure 10 shows the Energy-Time Curve (ETC) as obtained in the theatre hall. The Schroeder integration curve is also plotted and the two time instants T_1 and T_2 corresponding to the chosen sound levels are marked on that curve. Figure 11 shows the three-dimensional TDS plot of the room response taken in the time interval set by T_1 and T_2 of the ETC plot. The 3 D Reverb programme used these TDS data to calculate the reverberation time in various frequency bands. The final results obtained

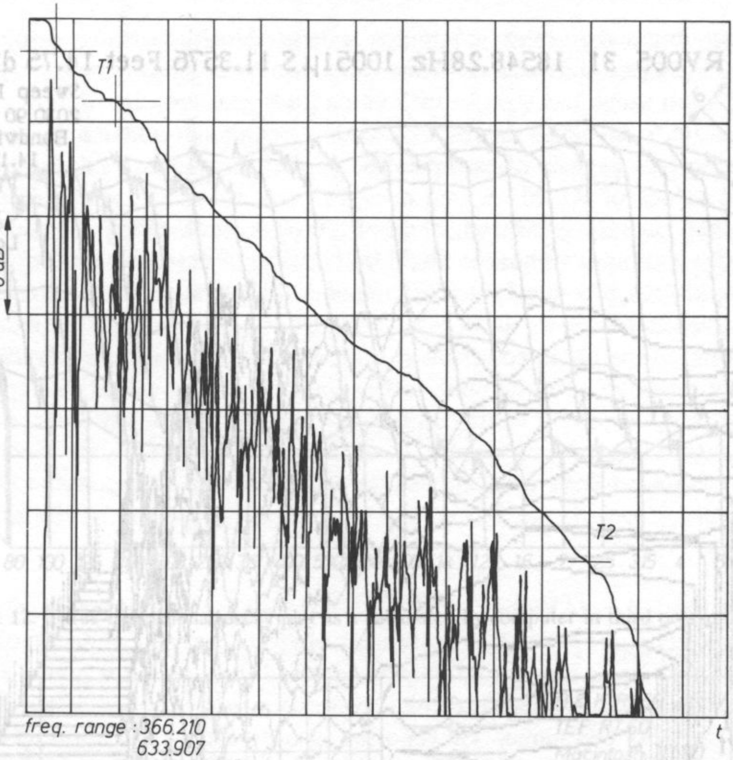

FIG. 10. Energy-Time Curve measured with TEF inside the Olympion theatre hall. Schroeder 1090783 usec, 1232.5844 feet, -30.10 dB; Sweep rate 20 Hz/s JOB 18; Time Span: 0usec, 1490489 usec; Dist Span: 0.0000E+00, 1.6843E+0.3 Feet

from an analysis in the third octave bands will be presented below and compared to the results given by the other two techniques.

The second technique was based on the Bruel and Kjaer Building Acoustics Analyzer Type 4418. This a portable battery-powered instrument capable of producing the third octave band limited random noise in the frequency range 100 Hz to 8 kHz (center frequencies). When used with a microphone and a sound source, the analyzer Type 4418 can calculate the reverberation time on-site and for each third octave band. This is achieved automatically by using the monitored decay curve and calculating the time required for a specified decay in sound level (there are three options available: -5 dB to -25 dB, -5 dB to -35 dB and -5 dB to -45 dB), subsequently multiplying this time (by 3, 2 or 1.5, respectively) to yield the reverberation time which by definition corresponds to a sound level decay of 60 dB. The analyzer type 4418 also offers sophisticated spatial, temporary and spectral averaging capabilities to enhance performance in adverse measurement conditions. In the measurements described here, three decay samples were taken for each third octave band and an average reverberation time was calculated. The above technique is well established and widely used in similar applications and hence it will serve as a reference in our case.

Finally, the third technique employed in the measurements was based on the use of a computer and a signal analysis programme for the computation of the reverberation

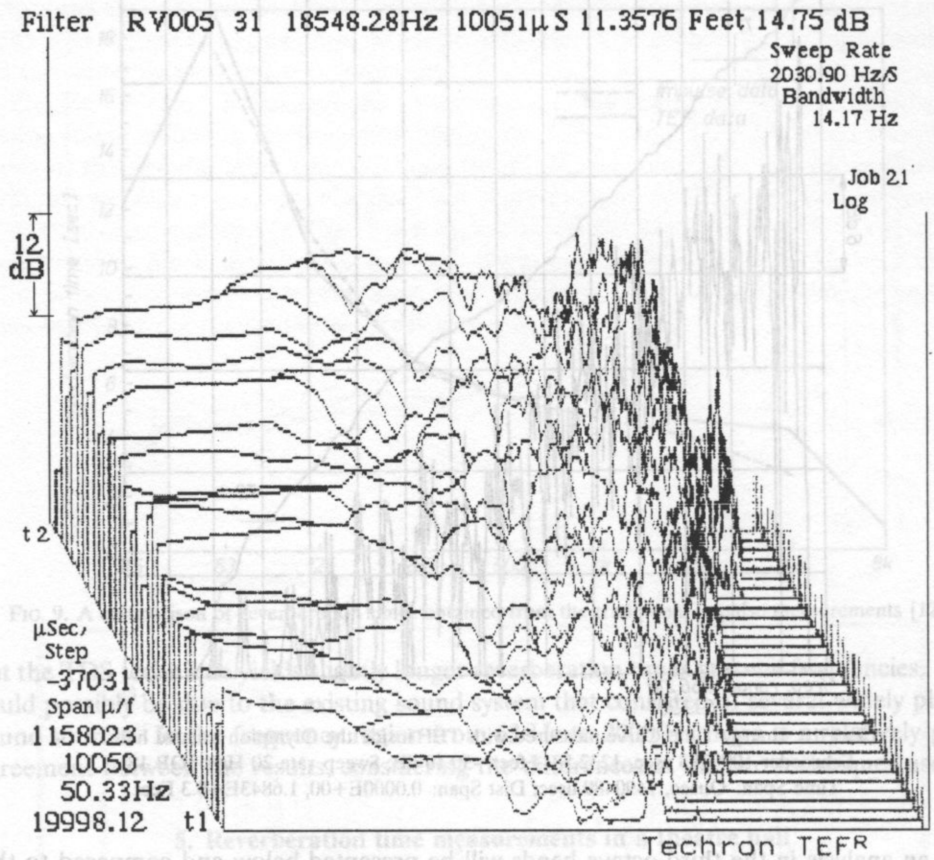

FIG. 11. Three-dimensional decay plot measured with TEF inside the Olympion theatre hall.

time in various frequency bands. The loudspeaker was fed with three successive bursts of pink noise and the responses were digitally recorded on the hard disk of a Macintosh IIx microcomputer. A dedicated signal analysis programme was taken written to process those responses by performing third octave frequency analysis of the decay transients. A three-dimensional decay plot obtained from such analysis is shown in Fig. 12. The reverberation time in each frequency band was calculated by measuring the time required for the sound level to fall from −3 dB to −23 dB relative to its steady-state value and then extrapolating it to find the time needed for a 60 dB fall. The final estimate of the reverberation time was then obtained by averaging the corresponding times calculated for each of the three recorded responses.

The reverberation times yielded by the three techniques described above, are presented graphically in Fig. 13. The low frequency end of scale is limited to 100 Hz according to the range attainable by the B and K 4418 analyzer. It is obvious that the measurements confirmed the suspected problems of the theatre hall. At lower frequencies the reverberation time is excessively long while in the frequency range typical for the human voice 500 Hz to 4 kHz it is nearly twice as long as the time regarded optimum for this type and size of room.

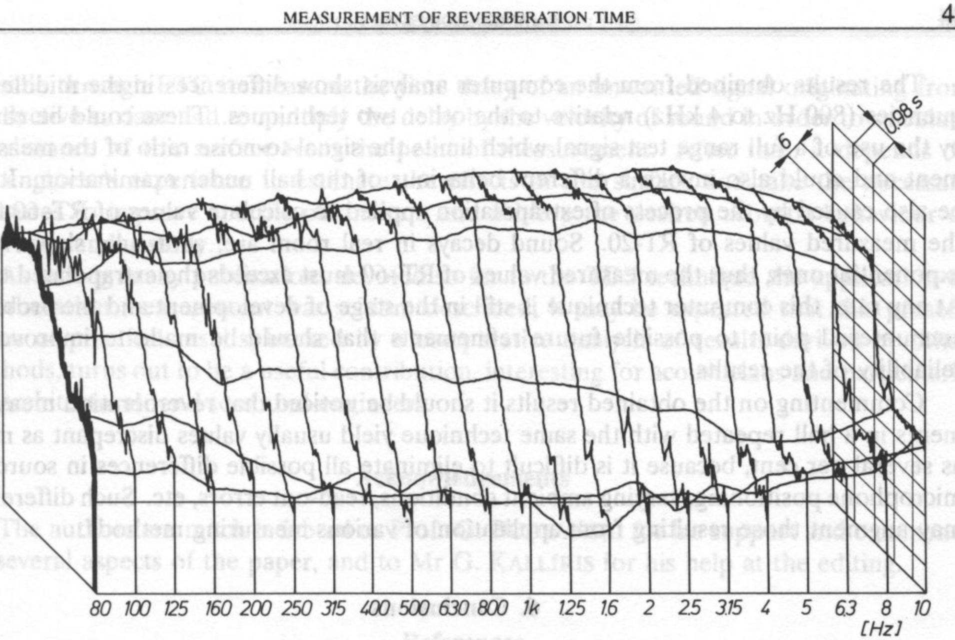

FIG. 12. Three-dimensional decay plot as a calculated by computer in third octave bands.

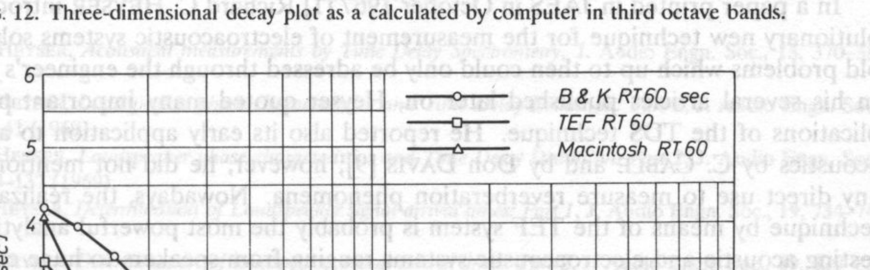

FIG. 13. Comparison between the reverberation times obtained from the three techniques.

Comparing the curves of Fig. 13, it can be seen that TEF system and B and K Type 4418 analyzer gave fairly similar results at frequencies above 250 Hz, a proof that the TDS technique can be used in such applications with equal confidence as the established techniques, while offering at the same time a level of measurement versatility that is almost impossible to achieve using a dedicated equipment. The somewhat increased difference in the reverberation times at frequencies below 200 Hz is probably due to the relatively limited frequency resolution of the TDS measurements, although this could not be verified using a different measurement setup.

The results obtained from the computer analysis show differences in the middle frequencies (800 Hz to 4 kHz) relative to the other two techniques. These could be caused by the use of a full range test signal which limits the signal-to-noise ratio of the measurement and could also invoke a different behaviour of the hall under examination. It can be also caused by the process of extrapolation applied to calculate values of RT–60 from the measured values of RT-20. Sound decays in real room are, as a rule, slower than exponential ones, thus the measured values of RT–60 must exceeds the extrapolated ones. At any rate, this computer technique is still in the stage of development and the problems encountered point to possible future refinements that should be made to improve the reliability of the results.

Commenting on the obtained results it should be noticed that reverberation measurements in a hall repeated with the same technique yield usually values discrepant as much as several per cent, because it is difficult to eliminate all possible differences in source or microphone positioning, varying ambient conditions, read-out errors, etc. Such differences may augment those resulting from application of various measuring methods.

6. Conclusions

In a paper printed in JAES in October 1967 [1] Richard C. HEYSER introduced a revolutionary new technique for the measurement of electroacoustic systems solving several old problems which up to then could only be adressed through the engineer's experience. In his several articles published later on, Heyser quoted many important practical applications of the TDS technique. He reported also its early application to architectural acoustics by C. CABLE and by Don DAVIS [9]; however, he did not mention explicitely any direct use to measure reverberation phenomena. Nowadays, the realization of this technique by means of the TEF system is probably the most powerful analytical tool for testing acoustic and electroacoustic systems ranging from speakers to huge concert halls. Therefore, its widespread use by manufacturers and engineers alike is symptomatic, as well as the numerous related papers which appear in specialized magazines and journals.

The general acceptance of TDS was expected considering the advantages that this technique offers. Its very good signal-to-noise ratio (S/N) is due to the control signal used in the measurements. Its ability to vary the time delay permits to simulate free-field conditions inside reflective surroundings. There is also the capability to vary continuously a parameter while monitoring the effects of this variation on other parameters. The technique allows fast and accurate measurements by relying on computer processing of the data. Finally, we should note the capability of performing traditionally complex measurements of electroacoustic systems and also of various characteristic acoustical parameters of listening rooms, reverberation characteristics included.

In the case of reverberation time measurements in particular, we have a portable analyzer having the size of a common personal computer and capable of generating its own control signal and calculating the reverberation time with 1/3 octave-band frequency resolution at any desired position inside a listening room, in contrast to traditional techniques.

The comparison between TDS and the traditional impulsive technique, discussed on the example given in the previous Section, shows that the TEF system is a convenient and versatile tool for measuring the reverberation time with negligible error. The three--dimensional display illustrates the variation of the sound level at all frequencies. It is even possible through ETC to measure the time delay of an unwanted signal originating from a reflective surface and to multiply the delay by the velocity of sound in order to calculate the distance of this surface from the point of measurement. After that, it depends on the engineer's experience to estimate the effects of this surface and take the necessary measures to improve specific parameters and achieve the desired acoustic behaviour of the room under study.

As among many publications devoted so far to the TDS technique the application to reverberation measurement was seldom described, it may be expected that this presentation of practical results, backed by a comparative analysis of results derived by other methods, turns out to be a useful contribution, interesting for acousticians and particularly for architectural- and to sound-engineers.

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References

[1] R. C. HEYSER, *Acoustical measurements by Time Delay Spectrometry*, J. Audio Engn. Soc., **15**, 370–382 (1967).

[2] R. C. HEYSER, *Loudspeaker phase characteristics and Time Delay Distortion: Part 1*, J. Audio Engn. Soc., **17**, 30–41 (1969).

[3] R. C. HEYSER, *Loudspeaker phase characteristics and Time Delay Distortion: Part 2*, J. Audio Engn. Soc., **17**, 130–137 (1969).

[4] R. C. HEYSER, *Determination of Loudspeaker signal arrival times: Part 1*, J. Audio Engn. Soc., **19**, 734–743 (1971).

[5] R. C. HEYSER, *Determination of loudspeaker signal arrival times: Part 2*, J. Audio Engn. Soc., **19**, 829–834 (1971).

[6] R. C. HEYSER, *Determination of loudspeaker signal arrival times: Part 3*, J. Audio Engn. Soc., **19**, 902–905 (1971).

[7] H. BIERING, O. Z. PETERSEN, *System analysis and Time Delay Spectrometry Parts 1 and 2*, Bruel and Kjaer Technical Review, No. 1 and 2 (1983).

[8] *3 D REVERB Software Manual*, Techton. Crown International Inc., 1987.

[9] R. C. HEYSER, *Fundamental principles and some applications of Time Delay Spectrometry* (Posthumous Manuscript edited in an anthology of the works of Richard C. Heyser) Audio Eng. Soc., New York 1988.

[10] P. D'ANTONIO, J. KONNERT, F. BECKER, C. BILELLO, *Sound intensity and interaural cross-correlation measurements using Time-Delay Spectrometry*, J. Audio Engn. Soc., **37**, 659–675 (1989).

[11] P. D'ANTONIO, J. KONNERT, *Complex time response measurements using Time Delay Spectrometry*, J. Audio Engn. Soc., **37**, 674–690 (1989).

[12] D. E. MARSH, J. E. RANDOFF, A. TAYLOR, *Researching the Astrodome's acoustics*, Sound and Video Contractor, p. 16 (1990).

[13] J. VANDERKOOY, S. P. LIPSCHITZ, *Uses and abuses of the energy-time curve*, J. Audio Engn. Soc., **38**, 819–836 (1990).

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