Comparison of reverberation measurements using Schroeder's impulse method and decay-curve averaging method[a]

W. T. Chu

Division of Building Research, National Research Council of Canada, Ottawa, Canada K1A 0R6
(Received 17 June 1977; revised 8 November 1977)

Utilizing a digital acquisition system and minicomputer, two promising techniques for accurate determination of reverberation times have been studied in detail from the viewpoint of standard reverberation room tests. The first is Schroeder's "integrated impulse method," and special attention was given to the question of repeatability and the influence of signal-to-noise ratio on the successful application of the method. The second technique involves taking an ensemble average of a large number of logarithmic decay curves. It was found that, even for nonuniform decays, the average decay curves obtained by the second method compared well with those determined by the Integrated Impulse Method.

PACS numbers: 43.55.Mc, 43.55.Br

INTRODUCTION

An accurate determination of reverberation decay is important for both absorption measurements in reverberation chambers and the evaluation of concert hall acoustics. A brief review of some of the more important methods of reverberation measurement, developed and utilized since the time of Sabine, has been given by Broach and Jensen.[1]

The most common method in use is to excite the room with filtered random noise for a few seconds and then observe the decay of the sound field as plotted on a level recorder. This will be referred to as the "individual decay method." Its limited application to room acoustics has long been recognized because the true nature of the decay is often obscured by random fluctuations in the decay curves. For absorption measurements in reverberation chambers, a technique frequently used to minimize the effect of these fluctuations on the measured reverberation-time values is to repeat the experiment many times and average the results from the individual decay curves. To overcome this time-consuming procedure, many laboratories have developed apparatuses for more automatic evaluation, mostly by means of a computer. Some[2,3] involve computation of reverberation times from the slopes of the decay curves. Others[4] are just modern computerized versions of the chronograph method.

More than a decade ago Schroeder[5] proposed "a new method, which, in a single measurement, yields a decay curve that is identical to the average over infinitely many decay curves that would be obtained from exciting the enclosure with bandpass-filtered noise." This is true only for a particular room, source, and receiver arrangement. Use of this method may result in exceptionally smooth reverberation decay curves from which accurate determination of the initial slopes is possible. Thus it offers a great advantage in the evaluation of auditorium and concert-hall acoustics. In cases of sound-absorption measurement where additional spatial averages are required, however, it becomes less attractive in view of the stringent requirement of instrumentation. Based on Kuttruff and Jusofie's modified approach,[6] a commerical unit, the Reverberation Processor type 4422, has been produced by Brüel & Kjaer for this technique.

The method has not been adopted for standard absorption measurements. Recently, a comparison of the advantages of this method over those of the individual decay method for purposes of absorption measurement has been carried out by Behar,[7] but the conclusions seem to be debatable.[8]

The following will describe experiences at DBR/NRC in implementing Schroeder's "integrated impulse method" by means of a minicomputer and compare the results obtained with those obtained by another proposed method, the "decay-curve averaging method."

I. SCHROEDER'S INTEGRATED IMPULSE METHOD (IIM)

A. Theory and experimental method

It can be shown analytically[5] that the ensemble average $\langle s^2(t)\rangle$ of the squared decaying sound pressure at a receiving point in a room excited by filtered white noise is equal to a certain integral over the squared impulse response $r^2(\tau)$ for the room. Here the response includes effects associated with the transducers and any filters for shaping the spectrum of the noise. Mathematically the relation can be written as follows:

$$\langle s^2(t)\rangle = N\int_t^\infty r^2(\tau)\,d\tau \;, \tag{1}$$

where N is proportional to the power-spectral density of the noise in the frequency range measured.

The function $r(\tau)$ can be considered as the response of the room excited by a signal corresponding to the impulse response of the bandpass filter used, where the impulse response of the filter may be viewed as a modified tone burst with a spectrum identical to the spectrum of the filtered white-noise signal. This is true if the duration of the pusle used to excite the filter is much shorter than the period of the center frequency of the bandpass filter. Thus an identity exists between the ensemble average of the squared decaying sound pressure and an integrated squared tone-burst response.

---

[a]This paper was presented at the 93rd meeting of the Acoustical Society of America [J. Acoust. Soc. Am. 61, S33(A) (1977)].

 0001-4966/78/6305-1444$00.80

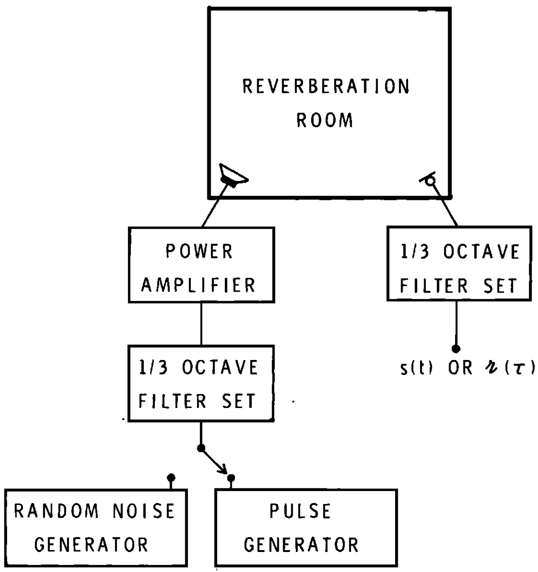

FIG. 1. Block diagram showing instrumentation set up for two methods of measuring reverberation time, one using filtered random noise and the other a filtered impulse to excite the room.

The function $r(\tau)$ can be obtained by a slight modification of the equipment used for conventional reverberation measurements. As shown in Fig. 1, a pulse generator is used instead of the random noise generator. The integral of $r(\tau)$, as prescribed by Eq. (1), can be evaluated by means of a digital computer or analog equipment. It seems that in Schroeder's original work a sizable digital computer was required to perform the integral because some "matched filtering" technique has to applied to $r(\tau)$ to improve the dynamic range of the decay curve.[9] Later, Kürer and Kurze[10] studied in detail three different analog techniques for evaluating the integral, including the same double-impulse excitation method proposed independently by Kuttruff and Jusofie.[6] None of the analog techniques, however, can exclude the influence of background noise (both acoustical and electronic) except by imposing an upper limit on the integration time, which is shorter than the expected reverberation time. As a result, the dynamic range of the decay curve is usually limited to about 25 dB. Over this range, Kuttruff and Jusofie[11] have produced good comparisons of decay curves obtained by the IIM and the individual decay method.

B. Effect of background noise

The only serious discussion about the effect of background noise was given by Kürer and Kurze.[10] Based on a simple quantitative analysis of one particular signal-to-noise ratio of 40 dB and some experimental results, they made practical suggestions for avoiding the effect of background noise by limiting the integration of Eq. (1) to a finite upper limit T_i which is about half the 60-dB reverberation time. In what follows an attempt is made to find a more general and systematic criterion for choosing T_i. An alternative method of handling the background noise is also proposed.

If $n(t)$ represents the acoustic and electronic background noise in the system, Eq. (1) is replaced by the following:

$$\langle s^2(t)\rangle^* = N\int_t^\infty [r(\tau)+n(\tau)]^2 d\tau$$
$$= N\int_t^\infty [r^2(\tau)+2r(\tau)n(\tau)+n^2(\tau)]d\tau \ . \qquad (2)$$

As $n(\tau)$ can be either positive or negative, the second term will integrate to zero. The third term always makes a positive contribution and significantly influences the decay curve at large τ where $r^2(\tau)$ has decayed to smaller values. After $r^2(\tau)$ has vanished, only $n^2(\tau)$ contributes to the integral. If the reverberation decay is truly exponential, the logarithmic decay curve will have the form indicated partially by the solid curves, labeled (1) in Fig. 2, i.e., a linear decay followed by a transition to another more or less linear portion with a much smaller slope. For longer times it will fall off steeply towards the end of the data record. The nearly linear portion and the rapid fall-off portion of the decay curve reflect the logarithmic behavior of a linearly decreasing function, which comes primarily from the $n^2(\tau)$ term. Thus, a systematic procedure for determining T_i seems possible. T_i is given by the point at which the decay curve just changes into the nearly linear portion in the latter part of the decay. To apply this technique, one should first perform the integration given by Eq. (2) over a record length much longer than the expected reverberation time in order to pick up the T_i point, as discussed above. One can then perform a second integration on the same record just up to T_i to give the proper decay curve.

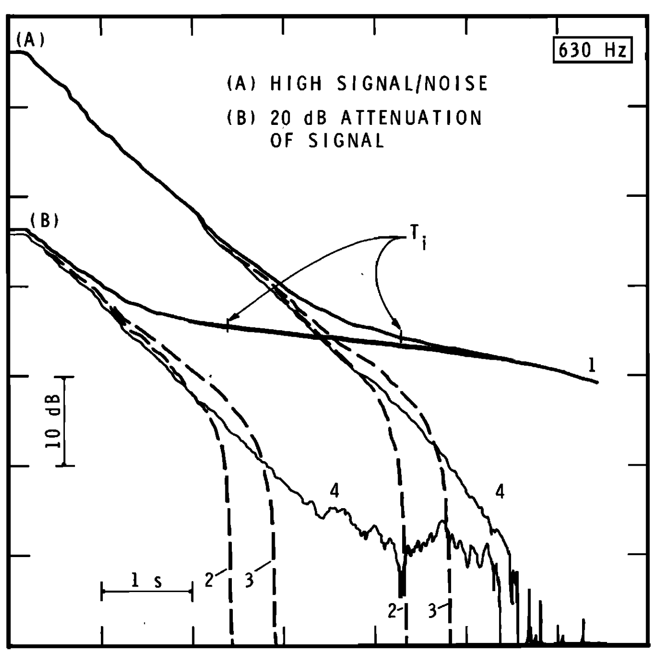

FIG. 2. Influence of background noise on the decay curves obtained by the integrated impulse method: (1)——using full record length, which is longer than the expected 60-dB reverberation time, (2) – – –using record length = T_i, (3)— — —using record length slightly longer than T_i, and (4)——using full record length with subtraction of background noise.

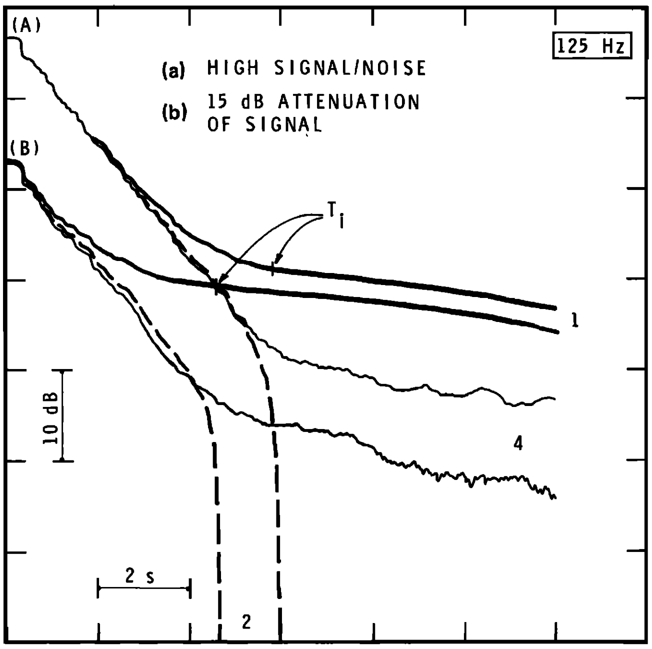

FIG. 3. Influence of background noise on decay curves obtained by the integrated impulse method: (1)——using full record length, which is longer than the expected 60-dB reverberation time, (2)- - -using record length = T_i, and (4)——using full record length with subtraction of background noise.

Another scheme for handling the background noise is to subtract its mean-square value from the original squared signal before perfroming the integration. Long after the response $r(\tau)$ has vanished, a temporal average value $\overline{n^2}$ of the background noise can be obtained, using identical settings of the instruments. The contribution of the residual background noise $(n^2 - \overline{n^2})$ will be small. Effectively, the process is presented by

$$\langle s^2(t)\rangle^{**} = N\int_t^\infty [r^2(\tau) + 2r(\tau)n(\tau) + (n^2(\tau) - \overline{n^2})]d\tau \ . \quad (3)$$

This scheme completely eliminates any uncertainty in choosing the finite upper limit of integration.

To test the proposed schemes, the IIM was implemented by means of a minicomputer with 32K memory, the Nova 820. The experiment was performed in a reverberation chamber equipped with both fixed diffusers and a rotating vane; volume of the room is 255 m^3. A detailed description of the facility is given in Ref. 12. The instrumentation setup is similar to that given in Fig. 1. A single microphone was used at the corner of the room, and the filtered microphone signal was digitized by a 12-bit A/D converter and then processed by the Nova 820 minicomputer. With the necessary program written in BASIC, a total of 8000 points could be used.

A proper sampling frequency has to be chosen, depending on reverberation time. As was pointed out by Atal *et al.*,[9] the sampling rate for this application can be slower than that given by the Nyquist criterion. For some high-frequency cases the sampling frequency had to be slightly lower than the Nyquist sampling condition because of the 8000 points and the reverberation-time limit.

The results shown in Fig. 2 demonstrate these various techniques for the 630-Hz $\frac{1}{3}$-octave band. Set (A) corresponds to a relatively large signal-to-noise ratio. Comparison of the peak of the measured response function $r(\tau)$ with the rms value of the background noise indicates a signal-to-noise ratio of about 50 dB. For Set (B) the microphone signal was attenuated by 20 dB before filtering and digitizing to enhance the effect of electronic noise. In both sets the thick solid curves [labeled (1)] represent the logarithm of the decay function $\langle s^2(t)\rangle^*$ given by Eq. (2), from which T_i can be determined. Dotted curves labeled (2) and (3) represent integration of Eq. (2) up to T_i and slightly greater than T_i, respectively. Light solid curves labeled (4) depict the logarithm of the decay function $\langle s^2(t)\rangle^{**}$ given by Eq. (3). Another set of results for the 125-Hz band is presented in Fig. 3. Here the signal-to-noise ratio is about 47 dB. For the first method to work, an accurate determination of T_i is required (Fig. 2). In this respect the scheme with background-noise subtraction is definitely superior and will be adopted for all subsequent investigations. Using this method, a dynamic range of 30–40 dB has been achieved for the decay curves.

C. Repeatability

As the decay curve obtained by the IIM represents the ensemble average over an infinite number of measurements, there is no doubt that the method will produce identical decay curves if repeated for a fixed room, source, and receiver arrangement. This has been confirmed experimentally by several detailed investigations.[1,10,11]

In many of the laboratories for sound-absorption measurement in North America, rotating diffusers are commonly employed to increase the diffusion of their test chambers. One would not expect that repeatable curves would be obtained for a fixed source and receiver arrangement in these rooms because conditions are continuously changed by the rotating diffuser. This is conclusively demonstrated in Fig. 4. The experiment was performed with an absorption specimen placed on the floor to create a nonlinear logarithmic decay. With the rotating vane stationary, even the minute details of the decay curve are reproduced in successive records. Decay curves show the expected variation as the vane rotates. It was noted that the variation was greater with the microphone placed away from the room boundaries rather than in the corner. Presumably, the microphone in the corner interacts with more modes than does the microphone located elsewhere in the room.

D. Advantages and disadvantages

The main advantage of the IIM is that a single measurement is sufficient to produce an ensemble average of the decay curves that would be obtained with bandpass-filtered noise as an excitation signal. The resulting smooth decay curve improves the accuracy of reverberation-time measurement and provides a means of detecting nonexponential decays. Thus the method is particularly suited to the evaluation of concert-hall

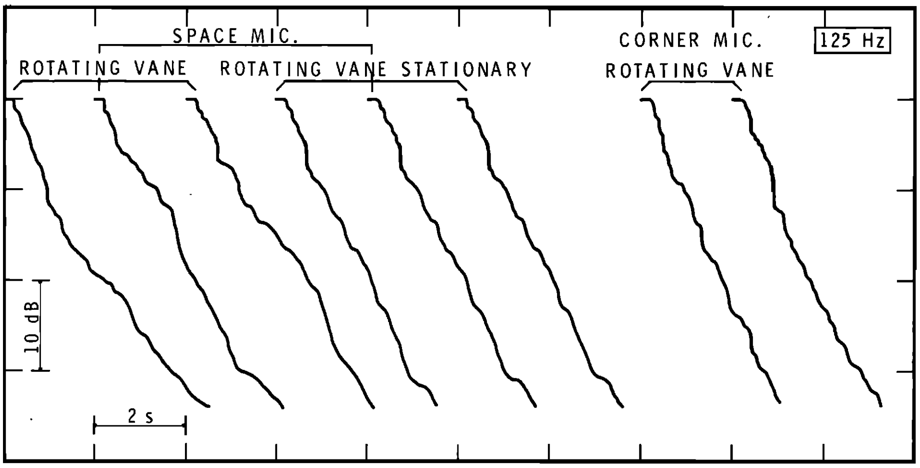

FIG. 4. Comparison of decay curves obtained by the integrated impulse method under two different conditions of the rotating vane in the room with an absorption specimen on the floor.

acoustics. It can provide definite comparison of different source and reciever positions in a room.

Like any impulsive technique, this method imposes stringent requirements on the instrumentation to provide a reasonably good dynamic range. It is important to match the duration of the impulse input to the band of frequencies to be analyzed. The impulse duration must be shorter than the period of the center frequency of the bandpass filter to produce the true impulse response of the filter for the driving signal. On the other hand, it cannot be too short or the signal strength will be weak, resulting in a decrease in signal-to-noise ratio. Finally, great care has to be exercised to avoid overloading of any of the instruments in view of the transient nature of the test signal.

II. DECAY-CURVE AVERAGING METHOD (DCAM)

A. Experimental techniques

As the name implies, this method involves literally taking an ensemble average of a finite number of decay curves for a fixed source and receiver arrangement. The scheme should work if the time interval between signal switch off and start of sampling of the pressure decay can be repeated with high accuracy. The signal level can vary between runs without affecting the shape of the average decay curve. Also, it is immaterial whether the mean-square pressure decay $\overline{p^2}(t)$ or the logarithmic decay is averaged, because the error involved in the averaging process affects every point on the decay curve similarly, except at very low signal levels where the bias effect of background noise becomes important. Averaging of the logarithmic decay curves was chosen for the present investigation because of convenience; the output from the General Radio $\frac{1}{3}$-octave real-time analyzer is given in decibels.

In order to compare results with the IIM, identical instrumentation (Fig. 1) was used, except that $\frac{1}{3}$-octave-filtered random noise was used to excite the room. Initially the filtered microphone signal was detected by means of a true rms device (Analog devices model 441) with an averaging time constant of 10 ms. The output from the rms detector was sampled by means of the A/D converter at intervals corresponding to about three times the averaging time constant.

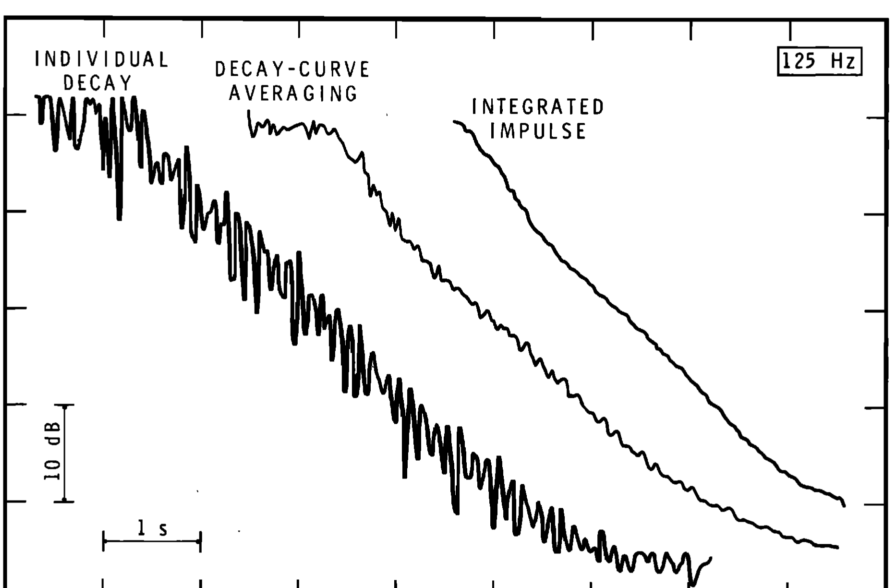

FIG. 5. Comparison of decay curves obtained by three different techniques at the corner of the room with an absorption specimen on the floor and rotating vane not in operation.

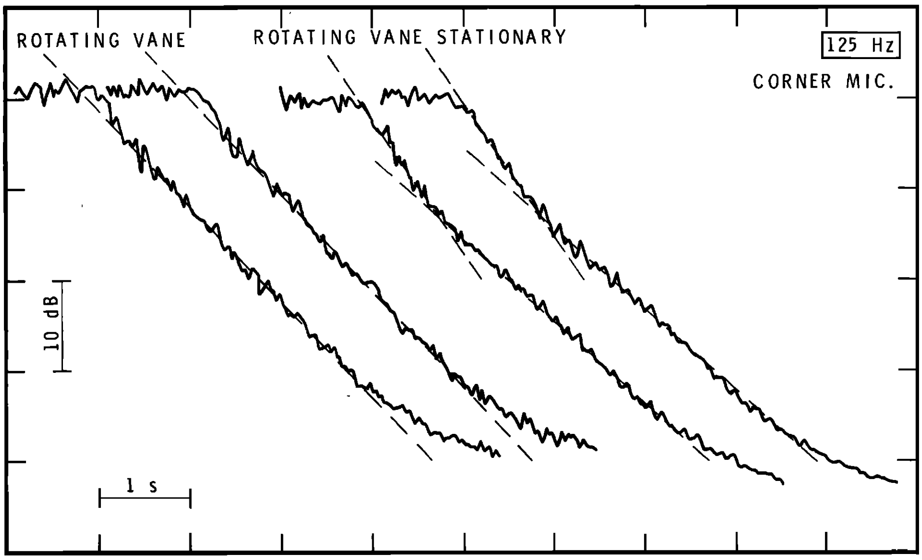

FIG. 6. Comparison of decay curves obtained by the decay-curve averaging method under two different conditions of the rotating vane in the room, with an absorption specimen on the floor.

To provide a known time reference for the start of the decay process, switching off of the random noise source must be controlled by the computer. In the present setup a control signal was given by the computer to a pulse generator, which held the noise source on for 9 s, then turned it off. Slightly before the end of this interval the A/D converter was initiated to sample the rms detector output at a rate of 30 samples per second. A logarithmic decay curve was computed and stored in the computer. The next decay curve was then added to the stored one point by point to generate an intermediate average curve. The process continued until a predetermined number of curves were averaged. To determine the number of repeated runs required, the successive average curves were displayed on a cathode-ray-tube display unit as the averaging process continued. Even at the 125-Hz band a total of 30 repeated runs was found to be adequate. The number required becomes progressively smaller for higher-frequency bands, although for convenience 30 runs are normally used. The final average decay curve was then reproduced on an $X-Y$ plotter.

Figure 5 shows a comparison of the decay curves obtained by the three different techniques under the same conditions. The individual decay method gave a single logarithmic decay similar to that which would be obtained by a level recorder. It can hardly show the nonlinear nature of the decay. A comparison of the curves produced by the DCAM and the IIM confirms belief that present-day electronics can give very precise timing control to make the proposed scheme possible. The DCAM can average out the random fluctuations without affecting the general characteristics of a decay curve.

B. Repeatability

As the DCAM uses a true averaging technique, any time-varying influence due to the rotating vane can also be averaged out. Figures 6 and 7 compare the average decay curves (over 30 decays) obtained from repeated

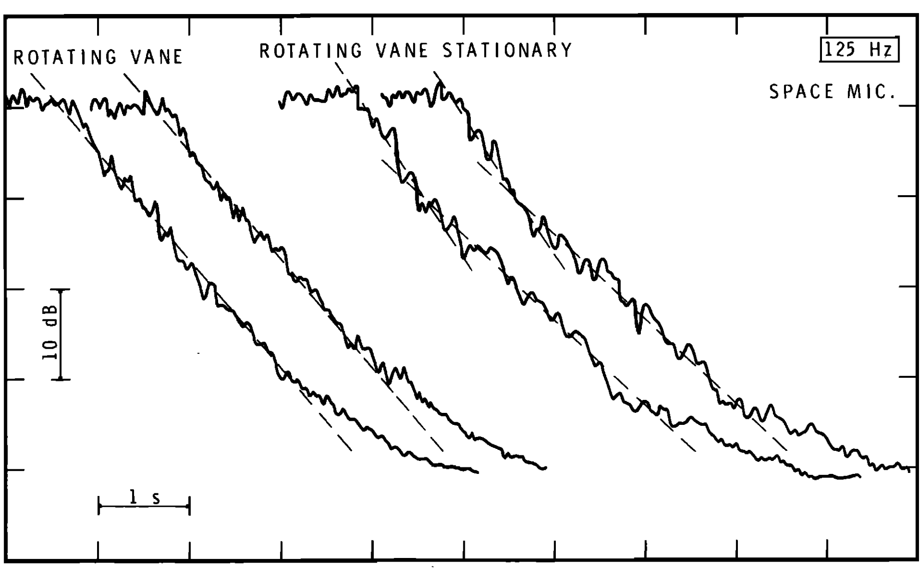

FIG. 7. Comparison of decay curves obtained by the decay-curve averaging method under two different conditions of the rotating vane in the room, with an absorption specimen on the floor.

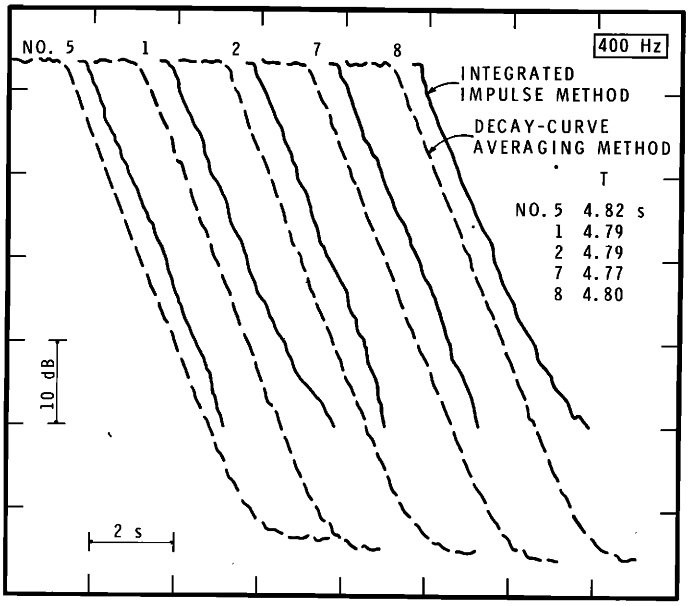

FIG. 8. Comparison of decay curves obtained by the two different techniques at five different locations in the room, with an absorption specimen on the floor and rotating vane in operation. Average reverberation time obtained by the individual decay method was 4.83 s at No. 5 microphone position.

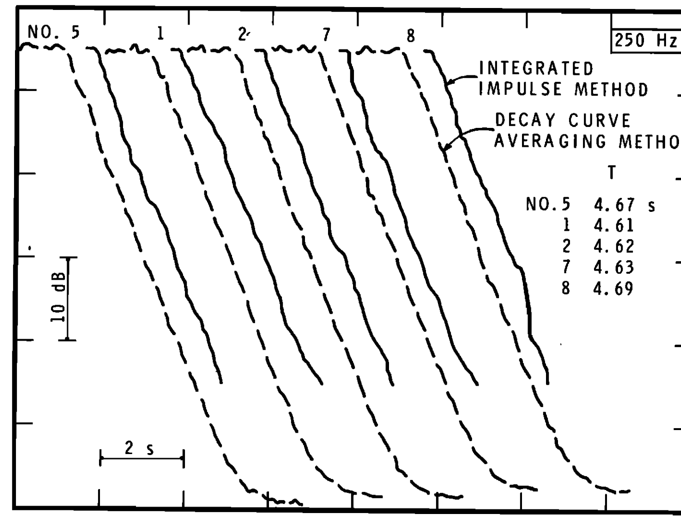

FIG. 9. Comparison of decay curves obtained by two different techniques at five different locations in the room, with an absorption specimen on the floor and rotating vane in operation. Average reverberation time obtained by the individual decay method was 4.71 s at No. 5 microphone position.

runs for two conditions of the rotating vane at two microphone positions, respectively. Parallel lines are superimposed to enhance the similarity between the decay curves. Results indicate that good reproducibility of average decay curves can be obtained with the DCAM, even in the presence of a rotating diffuser. These preliminary investigations clearly show the advantage of using a rotating diffuser in a test room to increase its diffusion. Figures 6 and 7 also show that a microphone placed in the corner of the room can produce a smoother decay curve than one placed elsewhere in the room.

C. Advantages and disadvantages

Because a continuous random signal with a $\frac{1}{3}$-octave bandwidth is used, the DCAM can produce better dynamic range for decay curves than the integrated impulse method. Analysis of results can be performed with minicomputers having much smaller memory or can be done by means of any waveform averager. Owing to the true averaging technique, the method can be applied to test rooms with rotating diffusers. In view of its ability to average out random fluctuations without affecting the general characteristics of a decay curve, the method could also be used for evaluation of concert-hall acoustics, with only a small penalty of longer testing time.

III. PRACTICAL RESULTS

Practical applications of the IIM to room acoustics have already been given by Schroeder[5] and others.[1,10,11] This paper presents some useful applications of the DCAM to standard reverberation room tests. In particular, the dependence of reverberation time on microphone positions was studied, with a 2.44×2.44 – m^2 (8×8 ft^2) absorption specimen placed in the room. As in all standard tests, the rotating vane was in operation and placement of the microphones in the room followed the standard recommendation. A total of five microphone positions were used: one at the corner (No. 5) and the others (Nos. 1, 2, 7, and 8) scattered about the room. For this particular test the General Radio type 1926 multichannel rms detector was used with a $\frac{1}{10}$-s averaging time. The experiment was performed one band at a time and an ensemble averaging over 30 repeated runs used for all the bands investigated. For comparison purposes results obtained by the IIM are also presented. For the corner microphone, No. 5, only, an average of the reverberation times computed on 100 individual decay curves by the individual decay method was also obtained.

Figure 8 shows the set of results for the 400-Hz band.

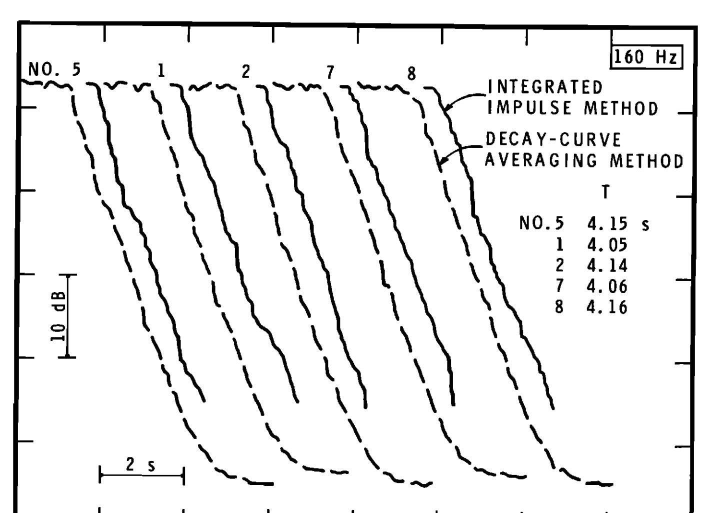

FIG. 10. Comparison of decay curves obtained by the two different techniques at five different locations in the room, with an absorption specimen on the floor and rotating vane in operation. Average reverberation time obtained by the individual decay method was 4.15 s at No. 5 microphone position.

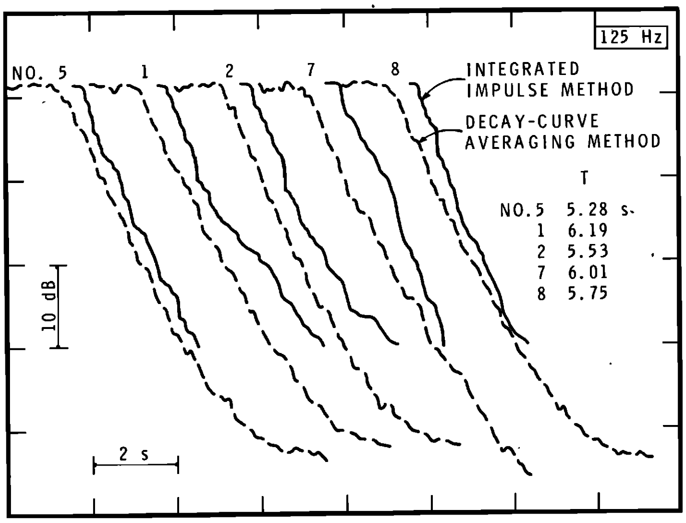

FIG. 11. Comparison of decay curves obtained by the two different techniques at five different locations in the room, with an absorption specimen on the floor and rotating vane in operation. Average reverberation time obtained by the individual decay method was 5.38 s at No. 5 microphone position.

It is apparent that at this rather high-frequency band the decay curves obtained by the IIM at different microphone positions showed noticeable variations because of the rotating vane effect. Those obtained by the DCAM, however, show very little difference. Similar plots for a few other frequency bands are shown in Figs. 9–11. To give an unbiased estimate of the reverberation time, a straight line was fitted to the linear portion of each decay curve obtained by the DCAM, starting 5 dB below the maximum level, by means of the least-squares technique. The resulting reverberation times are tabulated in the individual figures. Values for the No. 5 microphone position agree well with the average values obtained by the individual decay method. Except for the 125-Hz case, results indicate that reverberation-time measurements do not depend on microphone position in the test room. It is thus reasonable to conclude[13] that for frequencies higher than 125 Hz, which corresponds to a model overlap of about 1, sufficient diffusion has been achieved by means of stationary and rotating diffusers, and that a single microphone-position measurement at the corner is adequate. At 125 Hz, spatial average using a number of microphone positions is still necessary.

IV. CONCLUSIONS

An extensive investigation of Schroeder's integrated impulse method together with a proposed decay-curve averaging method has been performed for reverberation measurements. Results show beyond any doubt that both methods are accurate and superior to the individual decay method.

The two methods are complementary. The first is best suited for investigations of spatial variations in a room, with the object of proceeding as directly as possible to the ensemble average for each position; the second method is better for standard room tests where rotating diffusers are often employed to improve diffusion and the object is to determine the space-average reverberation time for the whole room.

Preliminary results also indicate the usefulness of the second method for investigating the effectiveness of the rotating vane in improving the diffusion of test rooms.

ACKNOWLEDGMENT

The author wishes to thank T. D. Northwood for his suggestions and remarks and A. C. C. Warnock for his assistance in programming. This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

[1]J. T. Broch and V. N. Jensen, "On the measurement of reverberation," Brüel & Kjaer Tech. Rev. No. 4 (1966).
[2]N. F. Spring, "Automatic reverberation time measurement with the aid of a computer," Proc. 7th Int. Congr. Acoust. Paper 24-A2 (1971).
[3]T. W. Bartel and P. A. Schade, "Digital processing of decay rates for reverberant sound fields," Inter-Noise 74 Proc., 61–64 (1974).
[4]M. Baker, "An automatic reverberation time measuring system," Appl. Acoust. 7, 271–280 (1974).
[5]M. R. Schroeder, "New method of measuring reverberation time," J. Acoust. Soc. Am. 37, 409–412 (1965).
[6]H. Kuttruff and M. J. Jusofie, "Nachhall messungen nach dem verfahren der integrierten imputsantwort," Acustica 19, 56–58 (1967/1968).
[7]A. Behar, "Comparison of RT-measurements using the ISO and the Schroeder–Kuttruff measurement methods," Acustica 34, 46–47 (1975).
[8]H. Kuttruff, "Comments to 'Comparison of reverberation measurements using the ISO and the Schroeder-Kuttruff method,' " Acoustica 34, 48 (1975).
[9]B. S. Atal, M. R. Schroeder, G. M. Sessler, and J. E. West, "Evaluation of acoustic properties of enclosures by means of digital computers," J. Acoust. Soc. Am. 40, 428–433 (1966).
[10]R. Kürer and U. Kurze, "Integrationsverfahren zur Nachhallanswertung," Acustica 19, 313–322 (1967/1968).
[11]H. Kuttruff and M. J. Jusofie, "Messungen des Nachhallverlaufs in mehreren Räumen, ausgeführt nach dem Verfahren der integrierten Impulsantwort," Acustica 21, 1–9 (1969).
[12]W. T. Chu, "Precision of sound pressure level measurements in a reverberation room," Natl. Res. Coun. Can., Div. Build. Res., BR Note 101 (1975).
[13]ASTM C 423-77, "Standard Method of Test for Sound Absorption of Acoustical Materials in Reverberation Rooms," paragraph 5.5.