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On the New Reverberation Chamber with Nonparallel Walls (Studies on the Measurement of Absorption Coefficient by the Reverberation Chamber Method, II)

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The details of the new reverberation chamber are given. It has a volume of and is surrounded by nonparallel walls. The results of model room experiments previously reported have been used to determine the shape and volume of this chamber. At 500 cps., the reverberation time of empty chamber was 22 seconds. The position of the microphone and the sound absorbing material did not affect the reverberation time of this chamber. This fact would show that the sound field of this chamber would fulfill the requisite for the diffuse sound field which is the premise of the reverberation chamber method.

§1. Introduction

From the fundamental researches described in the Report I [1], it has come to be clear that to make the shape of a reverberation chamber irregular is one of the effective means to get diffuse sound field which is indispensable for a reverberation chamber. Furthermore, relation between the size of the chamber and the uniformity of the sound field has been investigated. Based upon the results of these researches, a new reverberation chamber was constructed. This chamber has a volume of $513 m^3$ and is surrounded by nonparallel walls.

We inquired into the various characteristics of this chamber without sound absorbing materials. Further we pursued the effects of the warble tone and the loudspeaker upon the above characteristics. It was experimentally proved that the reverberation time of the chamber was longer than 20 seconds at 500 cps. and that the fluctuation of repeatedly measured reverberation time under the same condition was quite small. It was also confirmed that this was true in any part of the chamber.

However, when a sound absorbing material is put into the chamber to measure the absorption coefficient, the sound field would be different from that when the chamber is empty. Thus, special regard has been paid to the position of the sample material and the arrangement of the microphone in the conventional reverberation chambers.

The effect of the several factors affecting the sound field of our new reverberation chamber was investigated. As for the sample materials, we selected fibrous acoustic tiles and mineral wool board as typical examples from the viewpoint of the magnitude of absorption coefficient and its frequency characteristics. The results of these experiments showed that the position of the microphone and the sample material did not affect the absorption coefficient. This fact would show that the sound field of this chamber would fulfill the requisite for the diffuse sound field which is the premise of the reverberation chamber method.

§2. Construction of the Reverberation Chamber

2.1. Design and construction of the reverberation chamber

Since the irregular chamber used in the three-dimensional model room experiments was found more suitable as a reverberation chamber than a rectangular one, we designed a chamber after this irregular model. Next, the dimensions of the chamber was determined by consideration of the lowest frequency to be measured, which was around 60 cps. in this case. For this purpose, it was decided to make the frequency of 2000 cps. in the model chamber correspond to 100 cps. in the actual chamber. Accordingly the length of each side of the chamber was made 20 times as long as that of the model chamber, and thus the chamber of about 500m^3 became necessary. On the other hand, if the volume of the chamber is V, and the surface area is S, the number of normal modes ΔN in the frequency range between ν and $\nu+\Delta\nu$ is approximately given by [2)]

$$\Delta N \approx \left(\frac{4\pi V}{c^3}\nu^2 + \frac{\pi S}{2c}\right)\Delta\nu\,.$$

If the number of normal modes is calculated in the rectangular chamber (the ratio of the sides is 1.00 : 0.80 : 0.64) under the conditions of $V = 500\text{m}^3$, the number of normal modes included within a 1/3 octave band with center frequencies of 60 and 100 cps. are 9.5 and 38.4 respectively. This shows that the chamber dimensions as large as these are necessary from the viewpoint of the number of normal modes.

Next, the finish of the interior of the reverberation chamber offers an important problem as to the accuracy in measurement. Conventionally, the wall surfaces are finished with concrete (plastered or painted), parquet tiles, etc. We decided to adopt the polished concrete, taking into consideration the fact that its sound absorption is small and its maintenance is easy due to small quality change caused by time element.

Important data for this chamber which was made so as to match the previously mentioned conditions are shown in Table I. Dimensions of the chamber is given in Fig.1 and photo Fig.2 shows the interior of the chamber.

Table I. Details of the reverberation chamber

Volume	513 m^3
Surface area	382 m^2
Shape	Nonparallel Walls
Wall thickness	40 cm
Wall surface material	Steel - framed concrete with polished concrete

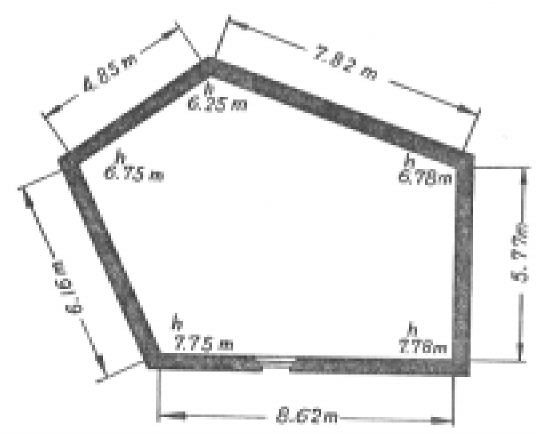


Fig. 1. Plan of the reverberation chamber. *h* shows the height of each corner.

2.2. Reverberation time measuring apparatus

The most important section of the rever-

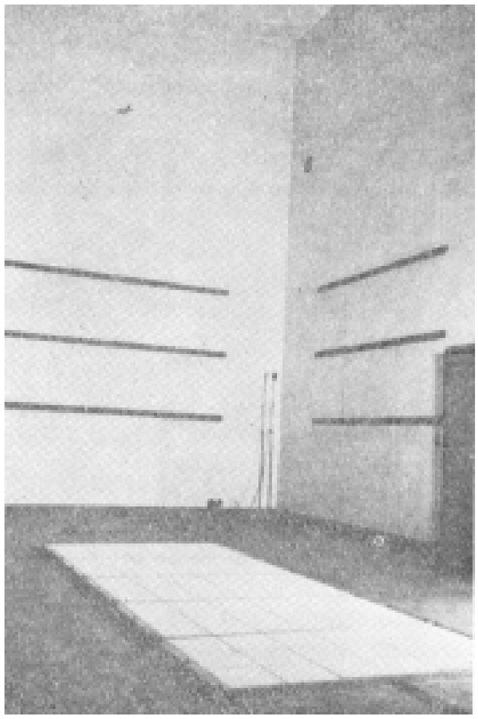


Fig. 2. Interior of the reverberation chamber.

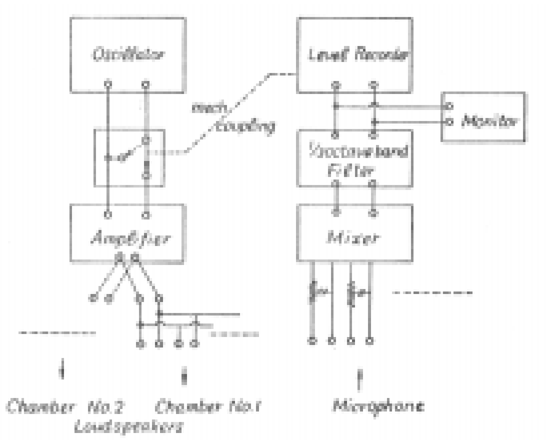


Fig. 3. Block diagram of the apparatus for the measurements of reverberation time.

beration time measuring apparatus is the one which measures or records the decay process of sound. Here, we used a high speed level recorder for this purpose. Furthermore, since the reverberation time to be measured is relatively long, the make and break of the simple mechanical contact point, which work in linkage with the level recorder, were adopted for the switching-on and -off of the oscillator. The block diagram of the measuring apparatus is shown in Fig. 3.

§3. Characteristics of the Empty Reverberation Chamber

3.1. Researches on measuring system

(i) *Characteristics of warble tone*

When the center frequency is v_0 , modulation swing $\pm\Delta_v$ and the modulation frequency α , the warble tone given by them has a spectrum consisting of $2\Delta v/\alpha$ components lined up at intervals of α cycles within the range of $v_0 \pm \Delta v$ [3]. If the dimensions of the chamber and the center frequency are given, the minimum permissible value of Δv is given by the condition that it should include sufficient number of normal modes to uniformize the sound field. Under the given conditions that v_0 equals 100 cps. and the number of normal modes equals 30, an inequality $\Delta v > 9$ results. It was also found that if Δv is made larger, unevenness in absorption within the range becomes sometimes intolerable. In the present experiments, Δv was made 10 percent of center frequency at lower frequencies and 50 cps. at higher frequencies.

Next, for the purpose of exciting all the normal modes within the range, the interval α of spectrum offers a problem. In the chamber with sharp resonant characteristics (that is, long reverberation time), some of the norma modes are not excited unless the intervals are sufficiently small. On the other hand, if α is so small that one sweep takes too long a time, the normal modes at the far end of frequency range are considerably decayed, and accordingly it means little to use warble tone. Such being the case, α must be decided in connection with the reverberation time of the chamber. A conventional rule for the suitable range of α is given by an inequality $8/T > \alpha > 4/T$ [4]. However, as will has far longer reverberation time than the ordinarily used ones, and consequently we thought it necessary to confirm the above inequality by the experiments as the first step.

An example of decay curves obtained by observing the variation with modulation frequency α is shown in Fig.4. The reverberation time T was 22 seconds. When α became more than 8, fluctuation of sound pressure level in the steady state became small and minute changes on the way of decay were not observed. However, large undulations were seen over the whole decay curves. When α is small, the fluctuation in the steady state became large but the decay showed a perfectly logarithmic curve (The ordinate in the records in a decibel scale and so the ideally exponential is recorded as the straight line). From these results, we came to the conclusion that the modulation frequency must be around $10/T \sim 20/T$.

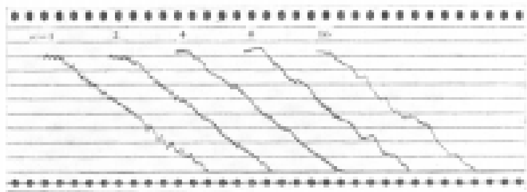


Fig. 4. Variation of decay curve with modulation frequency of warble tone.
$v_0 = 500\text{c/s},\ \Delta_v = 30\text{c/s}$

(ii) *Selection of loudspeakers*

A loudspeaker was selected by considering the following two points. That is, it has a sufficient power output so as to show at least the decay curve of 40 decibels before reaching the noise level, and also it is intended to decrease the added absorption due to the loudspeaker.

At first, we used a 25 cm cone type loudspeaker which was housed in a closed enclosure of $0.18\,\text{m}^3$ cubical content. In this condition, the minimum resonant frequency of the loudspeaker is around 50 cps. There was observed an absorption around 100 cps. caused probable by the vibration of the closed enclosure panels. As a result, the decay curve showed a slight bend around this frequency and the reverberation times derived from the decay curves measured under the same conditions showed inconsistent values.

In the second experiment, a horn-speaker driver unit was used. It did not produce any trouble regarding the measurement of the decay curve at the frequencies higher than about 100 cps., though the power output was a bit insufficient. Further, the reverberation time showed about the same values in each experiment, and the reverberation time became remarkably longer, especially at frequencies below 300 cps.

Then the reverberation time was measured at 125 cps. with several types of loudspeakers.

Table II. Effects of loudspeaker on the reverbera - tion time. $v_0 = 125$ cps., $\Delta_v = 15$ cps., $\alpha = 1$.

Type of loudspeaker	Average of 10 measurements	Standard deviation
Horn - speaker unit	46.0 sec	0.35 sec
25 cm cone (naked)	40.0	0.90
25 cm cone (with bufflle board of 50 cm × 50 cm)	39.0	1.2
20 cm cone (built in a closed cubical enclosure of 0.027 m^3)	35.5	1.5
25 cm cone (built in a closed enclosure of 0.18 m^3)	25.7	1.2

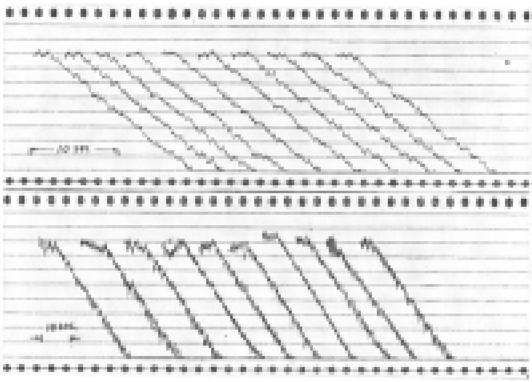


Fig. 5. Decay curve for empty chamber.
Upper : $v_0 = 500$c / s, $\Delta v = 30$c / s, $\alpha = 1$
Lower : $v_0 = 125$c / s, $\Delta v = 15$c / s, $\alpha = 1$

The results of these experiments are shown in Table II which includes the average and standard deviation of reverberation times for ten measurements. From these experiments, it was decided to use the horn-speaker driver unit in most experiments.

3.2. Reverberation time and sound pressure distribution

(i) *Reverberation time*

Firstly, we measured the reverberation time of the chamber, using the horn-speaker unit as the source of sound. The examples of the decay curves measured respectively at 500 and 125 cps. are shown in Fig.5. These show an almost perfect logarithmic decay. Though we moved the microphone to five corners (including the position of the loudspeaker) and then to the center of the chamber, reverbera-tion times were scarecely affected by the changes of the position of the microphone at any frequency between 125 and 4000 cps.

Table III. Reverberation time of empty chamber (measured in June 21, 1956)

Frequency	Average	Standard deviation
125 cps.	46.0 sec	0.5 sec
250	37.0	0.5
500	22.5	0.2_5
1000	14.0	01_0
2000	10.0	01_0
4000	5.3_8	0.0_7

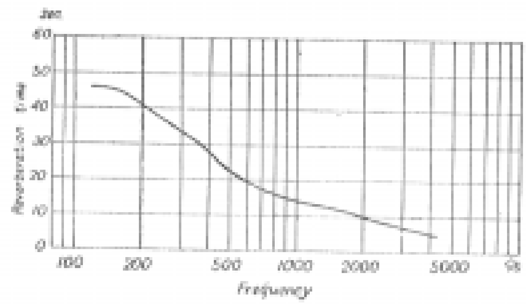


Fig. 6. Reverberation times for empty chamber.

Table IV. Sound pressure distribution in the chamber. Microphone position ; M_1.

Frequency	Position of microphone					
	M_1	M_2	M_3	M_4	M_5	M_6
125 cps.	5 db	2 db	0 db	2 db	1 db	0 db
250	1	1	1	0	2	0
500	1	− 1	−1	−1	0	0
1000	1	− 2	− 2	−1	0	0
2000	0	− 1	−1	−1	0	0
4000	0	− 2	− 2	− 2	0	0

Table III and Fig.6 show the results. Each row in Table III shows the average and standard deviation of the reverberation times for five measurements. Reverberation times at high frequencies depend largely on weather conditions. We shall report the detailed results on this subject in the near future.

(ii) *Sound pressure distribution*

The unevenness in sound pressure level in the steady state which are measured at six positions used preciously for measuring the reverberation time, is shown in Table IV. The marks which indicate the positions of the microphone in Table IV correspond to those of Fig.7 and will be used in all subsequent experiments. The difference of sound pressure level in different positions is quite small, being about 2 decibels even at 125 cps. except at the position of the loudspeaker.

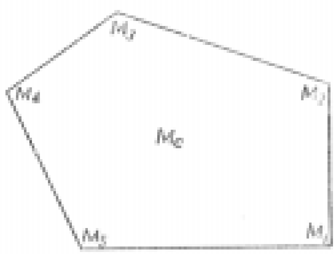


Fig. 7. Positions of microphone for reverberation measurements.

§4. Examinations of Various Factors that have an Influence upon the Measurements of Absorption Coefficient

As was discussed in Report I, the sound field in the reverberation chamber must fulfill the assumption of the diffuse sound field. The effect of several factors which might affect the sound field, was investigated in our reverberation chamber. We used the fibrous acoustic tiles and mineral wool board, as the sample materials for these experiments. The former has a large absorption at low frequencies, and on the contrary, the latter has a large absorption at high frequencies.

4.1. Patterns of decay curves

First, we examined the influence upon decay curves of two kinds of sample materials up to $30\,m^3$ fixed respectively on three or four faces of the reverberation chamber. The decay was completely logarithmic in this case as in the empty chamber, with in the frequency range of 125 to 4000 cps. Thus it was made clear that we could determine the reverberation time uniquely from this result. No extraordinary decay was observed at 200 cps. corresponding to the maximum absorption of the fibrous acoustic tiles and neither at high frequencies where a large absorption occured in case of the mineral wool. Fig.8 are examples of respective decay curves.

4.2. Effect of the position of the microphone

Using the sample material of 25 or ,
we investigated the effect of the position of the microphone on the absorption coefficient. The results are shown in Figs.9 and 10. It was found that, for any sample material used,

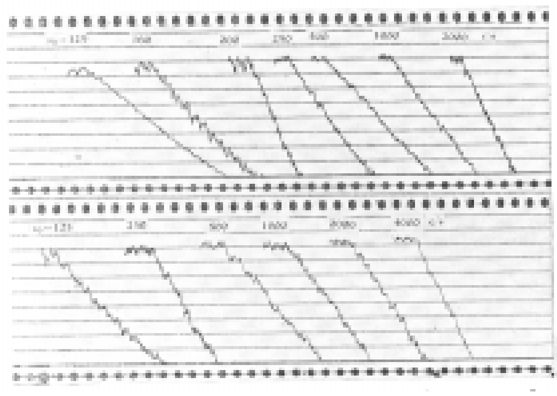


Fig. 8. Decay curves for the chamber, sample material present.
Upper : fibrous acoustic tiles, $10\ m^2$ (floor)
Lower : mineral wool, $16.5\ m^2$ (floor and two walls)

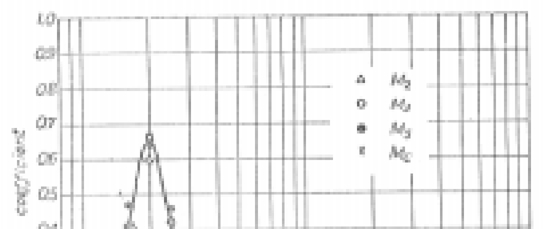


Fig. 9. Effect of microphone position on absorption coefficient of fibrous acoustic tiles. Sample area $25\ m^2$ (floor and two walls)

the position of the microphone exerted little influence upon the absorption coefficient. It is conspicuous that no effect upon absorption coefficient was found not only in any corner of the chamber but even in the center.

The uniformity of the reverberation time is the most important property of the reverberation chamber, and so we investigated this in detail. At the seven microphone positions which were arbitrarily chosen in the chamber, we measured twenty decay curves at each position. The average and standard deviation of reverberation times thus obtained are shown in Table V. Consequently, one microphone placed in an optional position may be enough for this kind of measurements.

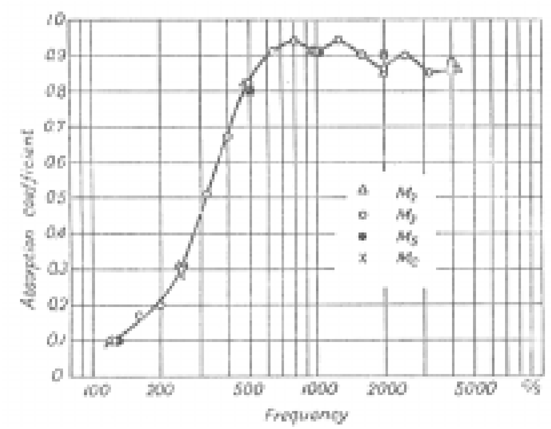


Fig. 10. Effect of microphone position on absorption coefficient of mineral wool. Sample area 30m^2 (floor and three walls)

Table V. Reverberation time of the chamber when the mineral wool 10m^2 was placed on the center of the floor. Seven microphone positions were chosen arbitrarily in the chamber and twenty decay curves were measured at each position.

Freauency	Average	Standard deviation
125 cps.	28.9 sec	0.97 sec
250	14.4	0.22
500	7.0_1	0.05
1000	5.8_0	0.07_2
2000	4.8_7	0.09_3
4000	2.8_3	0.08_4

4.3. Effect of area of the sample material

Next, placing the microphone in a fixed position, we examined the effect of the sample area upon absorption coefficient. Fibrous acoustic tiles having areas from 10 to 25 m^2 were fixed on three faces of the reverberation chamber. In case of mineral wool, the areas were from 3.3 to 30 m^2. The one with 30 m^2 area was fixed on four faces of the chamber, the one with 3.3 m^2 area was fixed on three faces of the chamber. The measured results of absorption coefficient are shown in Figs.11 and 12.

In case of mineral wool, the absorption coefficient obtained for the sample area of 3.3 m^2 became larger than that of other sample areas for the frequencies above 500 cps. This is considered to be the area effect explained by Chrisler's experiments[5). However, when the area is reduced to this extent, the measuring accuracy falls off extremely. Therefore, we are furthering a more precise investigation. However, in either of sample materials, no significant difference in absorption coefficient was found against the area change of more than 10m^2.

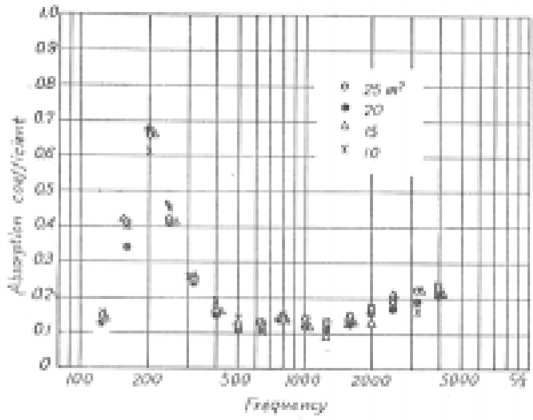


Fig. 11. Effect of sample area on absorption coefficient of fibrous acoustic tiles.

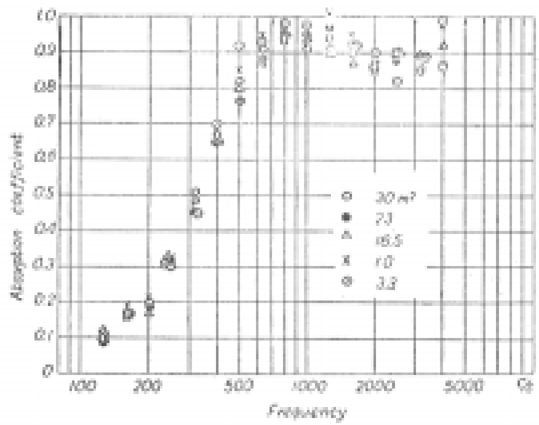


Fig. 12. Effect of sample area on absorption coefficient of mineral wool.

4.4. Effect of the mounting position of sample materials

We compared the absorption coefficients obtained respectively in three mounting positions of sample materials. In one case the sample material of   was separated on three faces, while in the other two cases the sample material of the same area was concentrated only on the floor (at floor center and edge). The results are shown in Figs.13 and 14. We found out that, in case of areas in this experiment, the absorption coefficient was not affected by the mounting position of sample material at any frequency.

4.5. Case of a large quantity of sample material being placed only on the floor

When mineral wool of 30 m^2 was placed on the floor, decay curves showed a bend for the frequencies between 1000 and 2000 cps. So, we measured the decay curves for various areas, within the range of 400 to 4000 cps. at intervals of 1/3 octave. The results are shown in Fig.15. As the area decreases, the range of frequency for which a bend takes place becomes narrower and it is not discernible below 16.5 m^2. We showed in the same figure the results obtained when the sample material was placed on three faces separately. In this case, the decay curves were all straight

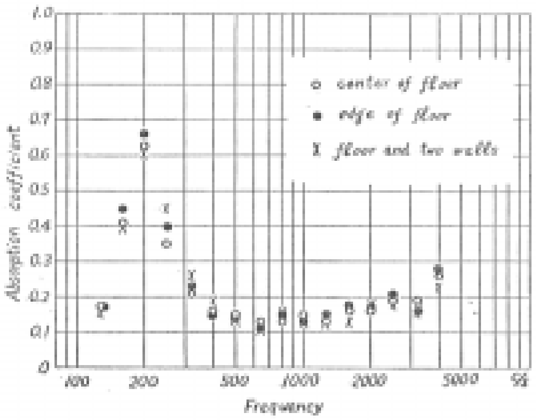


Fig. 13. Effect of sample position on absorption coefficient of fibrous acoustic tiles. Sample area 10m^2.

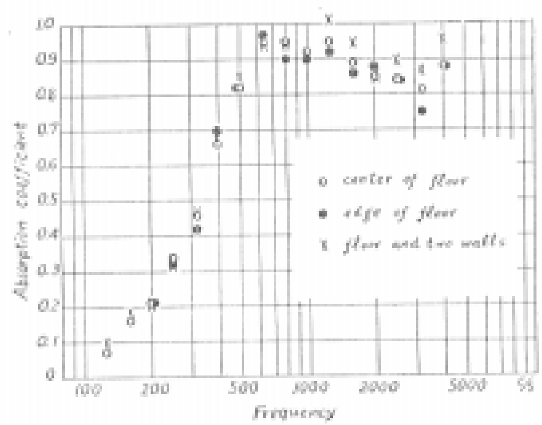
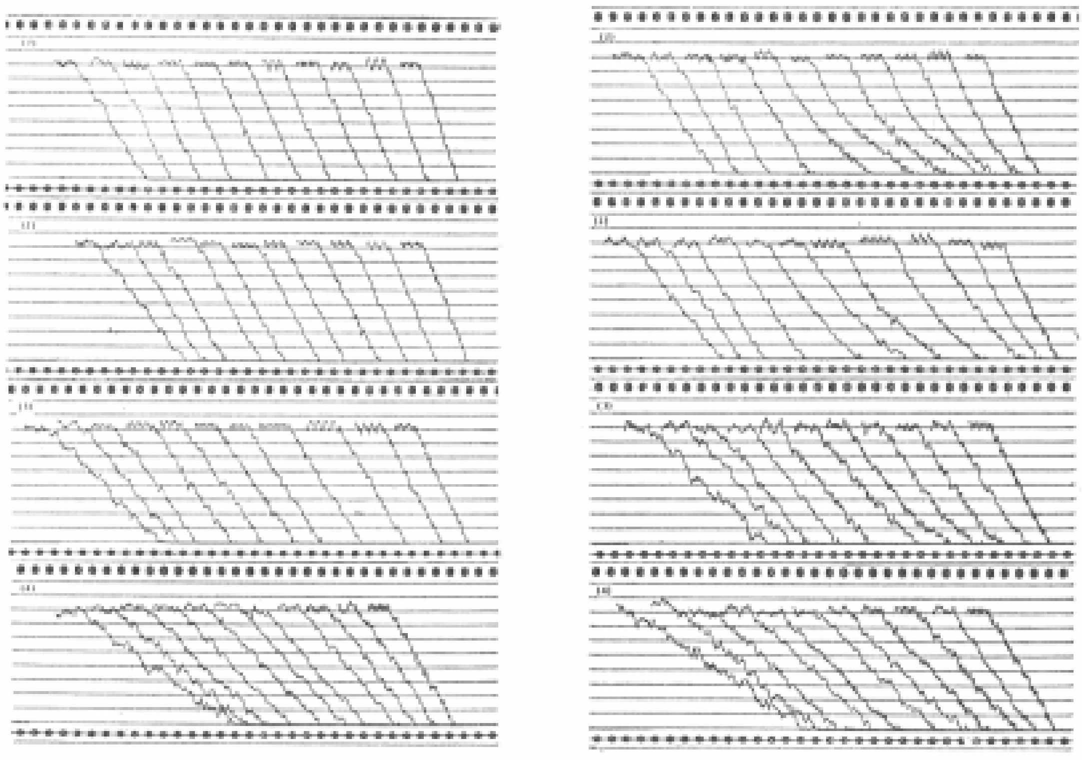


Fig. 14. Effect of sample position on absorption coefficient of mineral wool. Sample area 10m^2.



(a) (b)

Fig. 15 Decay curves for various frequencies. Curves obtained by changing the frequency from 400 to 4000 cps. in 1/3 octave step.

(a) mineral wool, floor and two walls.
(1) 30 m^2 (2) 23 m^2 (3) 16.5 m^2
(4) 10 m^2

(b) mineral wool, floors only.
(1) 30 m^2 (2) 23 m^2 (3) 16.5 m^2
(4) 10 m^2

lines, without any influence of area and frequency.

When the decay curve shows a bend, we can no longer assume that the sound field in the chamber is diffuse. However, we tentatively determined the absorption coefficient using the slope at the beginning part of the decay curve. Above 500 cps., where the absorption coefficient is large, it decreases as the area increases (Fig.16). This is rather an expected matter, because the sound field in the chamber differs from that in the empty chamber.

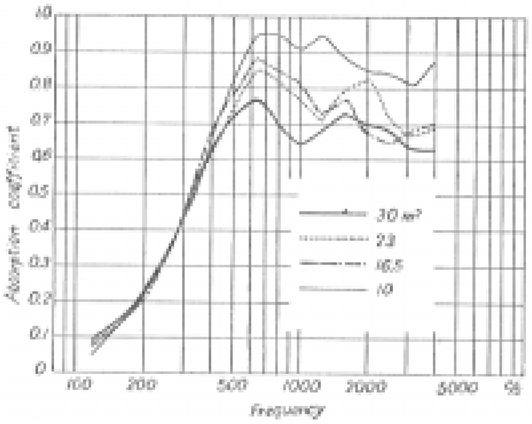


Fig. 16. Effect of sample area on absorption coefficient of mineral wool (sample placed on the floor onl)

§5. Conclusion

The outline of our newly constructed reverberation chamber and the various characteristics of this chamber concerning the absorption coefficient measurements are presented. The shape of the chamber was decided by the experiments conducted with the model rooms described in Report I, in order to fulfill the essential condition of diffuse sound field. The volume of the chamber was decided upon $513m^3$ for the purpose of measurements down to 60 cps.

Investigation on measuring system using the empty chamber, has shown that the absorption by the loudspeaker has a considerable effect on reverberation time at low frequencies and that the modulation frequency in warble tone has a considerable effect on decay curves. The reverberation time at 500 cps. is 22 seconds when the chamber is empty.

We investigated the various factors which were supposed to have influences upon the absorption coefficient measurements. The decay curve showed the logarithmic decay even when the sample material was present. The position of microphone was found immaterial in the measurements and also, when the sample material was about $10m^2$, the mounting position of the sample had no effect upon the absorption coefficient. These results would show that the sound field of this chamber would fulfill the requisite for the diffuse sound field, and that this chamber would have characteristics as expected from the fundamental experiments. This will bear witness to the fact that the sound field in our reverberation chamber has been much more improved than in the conventional ones, in which a special regard had to be paid in such things as to use several microphone positions and also to choose proper mounting position of sample materials.

This chamber was completed by the cooperation of Shimizu Construction Co., Ltd. Members of the Acoustical Material Association of Japan provided us with sample materials used for these researches. The fundamental experiments were conducted in cooperation with Mr. J. Sakagami. We should like to express our sincere appreciation for their cooperation.

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