

THE UNIVERSITY OF MICHIGAN
INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

REVERBERATION-ROOM ANECHOIC CHAMBER
TRANSMISSION-MEASUREMENT. TECHNIQUE

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FOREWORD

The work reported herein was conducted by the Acoustics and Seismics Laboratory of the Willow Run Laboratories of The University of Michigan. The Acoustics and Seismics Laboratory performs research in the areas of noise reduction, atmospheric acoustics, underwater sound, and seismics. The Willow Run Laboratories were organized to conduct a diversified program of research to help make the resources of The University of Michigan available to government and industry and to broaden the educational opportunities for students in the scientific and engineering disciplines. The program is carried out by a full-time Willow Run Laboratories staff of specialists in the fields of physics, engineering, mathematics, and psychology, by members of the teaching faculty, graduate students, and other research groups and laboratories of The University of Michigan.

This final technical report, written by S. S. Kushner and N. E. Barnett, details the work conducted under Contract No. AF 33(616)-3435, Project No. 1370, Aeroelasticity, Vibration, and Noise, Task No. 13465, "Standardization of Soundproofing Blankets." This research was sponsored by Wright Air Development Center, U. S. Air Force, with Mr. Joseph R. Bengoechea of the Dynamics Branch, Aircraft Laboratory, acting as task engineer. Supplemental Agreements Nos. 1-6 were made between Wright Air Development Center and The University of Michigan within the contract period, 15 February 1956 to 31 March 1959, during which time research activity was not continuous.

The research under this contract can be subdivided into three tasks performed in sequence. The first two tasks required sound-transmission measurements by a previously established method on two groups of aircraft materials furnished by WADC. The third and most recent task was the preliminary investigation of a revised sound-transmission test method deemed advisable because of the acoustic and physical nature of some of the aircraft samples submitted during the second task.

The authors wish to acknowledge the technical advice of G. B. Thurston.

J. C. Johnson, Head
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1. SUMMARY AND RECOMMENDATIONS

Experimental investigation has shown the futility of evaluating the acoustic transmission of stiffness-controlled samples on the Small-Sample Aircraft-Transmission-Text Apparatus. A promising method for evaluating the acoustic transmission of relatively stiff aircraft materials is the reverberant source room-anechoic termination method utilizing large samples. Exploratory experimental measurements were undertaken with the proposed method utilizing the new instrumentation recently provided by The University of Michigan. These preliminary experiments have been very encouraging and the method appears potentially capable of evaluating the acoustic transmission in great detail of samples possessing widely divergent physical characteristics. Moreover, calibration by means of absolute methods appears possible although this has not yet been attempted.

The Small-Sample Aircraft-Transmission-Text Apparatus remains satisfactory for blanket-type materials for which the test was designed. The larger transmission window in the reverberation room has been provided with an adapter to allow testing of appropriately flexible samples interchangeably by either test method, thereby allowing correlation after the new method has been fully calibrated. In the case of rigid samples to be tested by the reverberant source room-anechoic termination method, as large a sample size as possible up to a limit of five feet square should be provided, but it would be premature to standardize sample size, sample clamping, or instrumental parameters until some further testing is accomplished.

In order to finalize the new test method, some additional experimentation is recommended on all aspects of the method, but special emphasis should be placed on examining parameters of window size and the variation of apparent attenuation detail with surface density for a wide range of flexible samples, all approximating weight-law behavior. Following this, attention should be concentrated on evaluation of the calibration constants as a function of frequency and realization of absolute calibration.

2. BACKGROUND

Aircraft samples, requiring seven transmission tests, and constituting the first task, were submitted in July, 1956, and the test results were reported to WADC by letter dated 17 October 1956. The samples consisted of lightweight polyurethane-foam blankets and aircraft damping tapes. These samples were all light, nonrigid materials of the general types which the Small-Sample Aircraft-Transmission-Test apparatus had been designed to evaluate. [This apparatus has been described in detail previously (Refs. 1-4) and the present contract specifically requested its use. This apparatus is also described briefly in a later section of this report and is shown schematically in Fig. 1.] Thus it was considered that these first samples were correctly evaluated with respect to transmission, although the effectiveness of the vibration-damping capacity of the aircraft damping tapes in suppressing resonant transmission by fuselage panels could not be evaluated by this test method (Ref. 4).

Another group of samples was supplied in July and August, 1957, and the seventeen tests involving these constituted the second task mentioned above. A final report describing all 24 tests carried out during both the first and second tasks was issued in January, 1958, as University of Michigan Report 2490-1-F, Determination of the Sound Transmission Characteristics of Various Aircraft Soundproofing Materials, by S. S. Kushner and J. C. Johnson (Ref. 4), and it was assigned the designation WADC-TR-58-110. This second set of samples consisted of lightweight, quilted, insulation blankets, one aircraft damping tape and several aircraft honeycomb-type panels having various total thicknesses, skin thicknesses, core materials and core sizes. The honeycomb-type samples differed considerably from the types of samples which were intended to be tested on the Small-Sample Aircraft-Transmission-Test Apparatus; consequently, questions of validity and interpretation of test results arose. The problems were immediately brought to the attention of WADC by phone and letter before proceeding with testing. It was agreed to carry out the honeycomb-sample tests on the Small-Sample Apparatus in the manner reported in WADC-TR-58-110 (Ref. 4), and also to submit to WADC a proposal for the development of a revised test method more suitable for evaluating honeycomb-type and other variant samples.

A proposal for a new test method was submitted 16 April 1958 and, as a result, Supplemental Agreements Nos. 5 and 6 were issued to carry out such a test development. The necessary research is referred to as task three under this contract and the detailed description and discussion of this third task constitute the remainder of this report. Further discussion of the first and second tasks is unnecessary since they have already been reported to WADC in detail in WADC-TR-58-110 (Ref. 4).

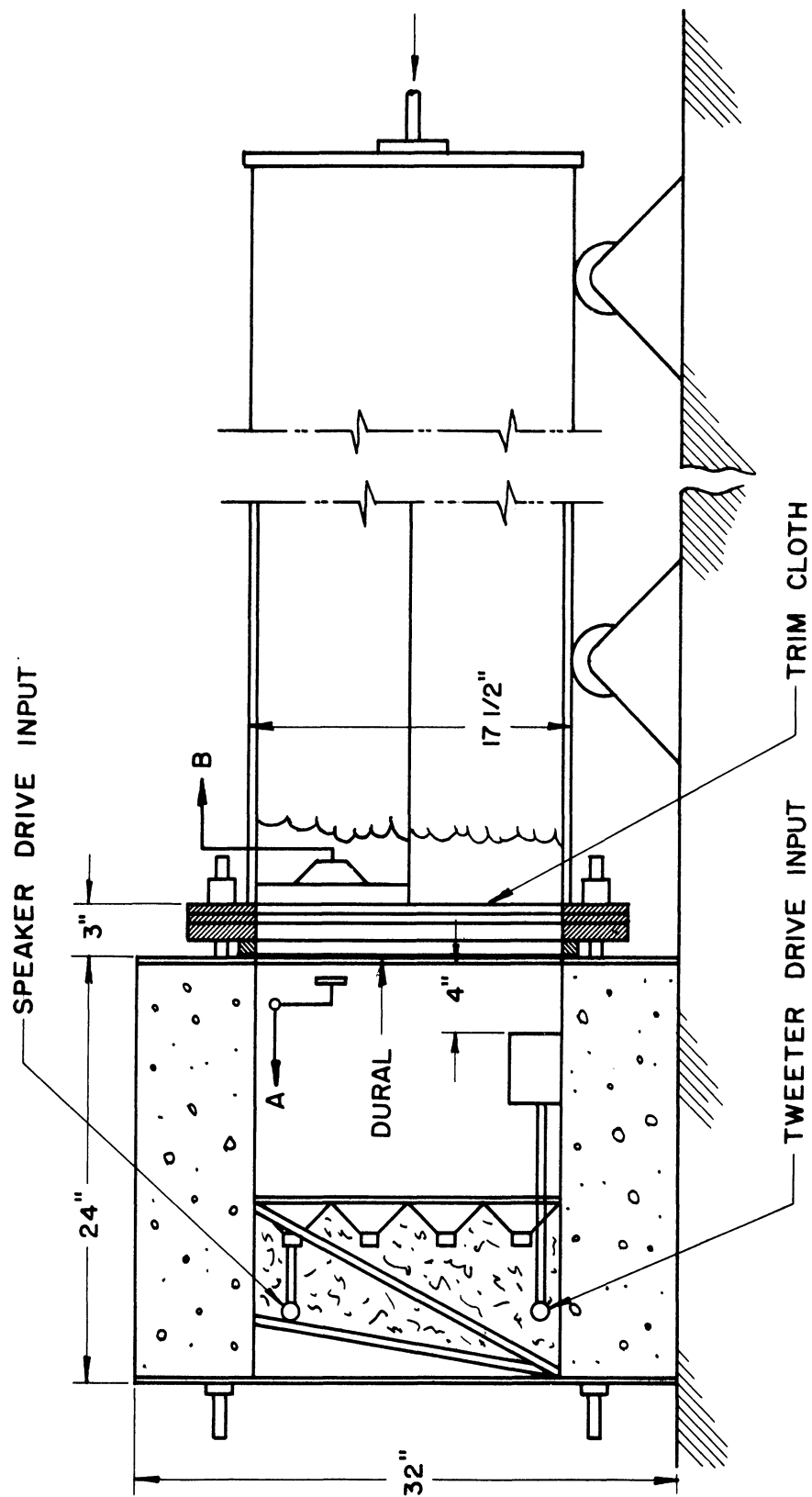


Fig. 1. Small-sample aircraft-transmission-test apparatus.

3. DISCUSSION

3.1 MEASUREMENT PROBLEM

The Small-Sample Aircraft-Transmission-Test Apparatus at The University of Michigan was developed by Dr. Paul H. Geiger during World War II. The method of measurement was equivalent to that developed by the Committee for Research on Sound Control at Harvard University and described in the December 15, 1941, report of the National Research Council Committee on Sound Control entitled Materials for Sound Control in Airplanes. The first formal report of test results obtained at The University of Michigan seems to have been issued in 1943 (Ref. 1), and since that time several reports have been issued covering both routine test results and improvements in the apparatus (Refs. 2,3,4). A similar apparatus and its underlying theory have been described in the general literature (Ref. 5).

The Small-Sample Aircraft-Transmission-Test Apparatus was designed specifically to evaluate the attenuation of sound transmitted through lightweight flexible aircraft soundproofing treatments such as were in use during the 1940s. A typical cross section of one of these treatments is shown in Fig. 2. Such a treatment consists of the aluminum skin of the aircraft, one or more flexible blankets of, say, fiberglas or kapok, often spaced away from the skin, and finally a covering of trim cloth. Sometimes a damping material such as "Stonefelt" was applied to the inside of the aluminum skin. Since the aluminum skin was common to all aircraft, it was simulated in the transmission test apparatus by a sheet of 0.020-in.-thick aluminum (see Fig. 2). For economy and convenience, a small sample size was desired, but on the other hand, the frequency range of measurement should lie above the major low-frequency resonances of the aluminum panel. These conflicts in requirements were resolved by selecting a 17.5-in.-square 0.020-in. aluminum panel mounted by clamping along its edges. For the undamped panel, some residual effects of panel resonance are observed up to about 150 cps. Above this frequency, the panel resonances are either absent or masked by other phenomena.

In reality, this aluminum panel has become the standard against which all treatments are evaluated. That is, the transmission of the plain aluminum panel is measured by means of the apparatus as shown in Figs. 1 and 3; then a sample consisting of blankets, trim cloth, etc., is inserted and the transmission is measured again. The decrease in transmission as a function of frequency is a measure of the treatment effectiveness.

In the transmission apparatus as shown in Fig. 1, a bank of sixteen small loudspeakers, excited in phase, is used as the acoustic source over most of the frequency range from 50 cps to 9,000 cps. (Above 5,000 cps, a tweeter unit is often necessary in order to supply enough acoustic energy.) At the lowest frequencies, the acoustic signal impinging on the aluminum panel is practically a normal-incidence plane-wave signal except for variations in speaker efficiency.

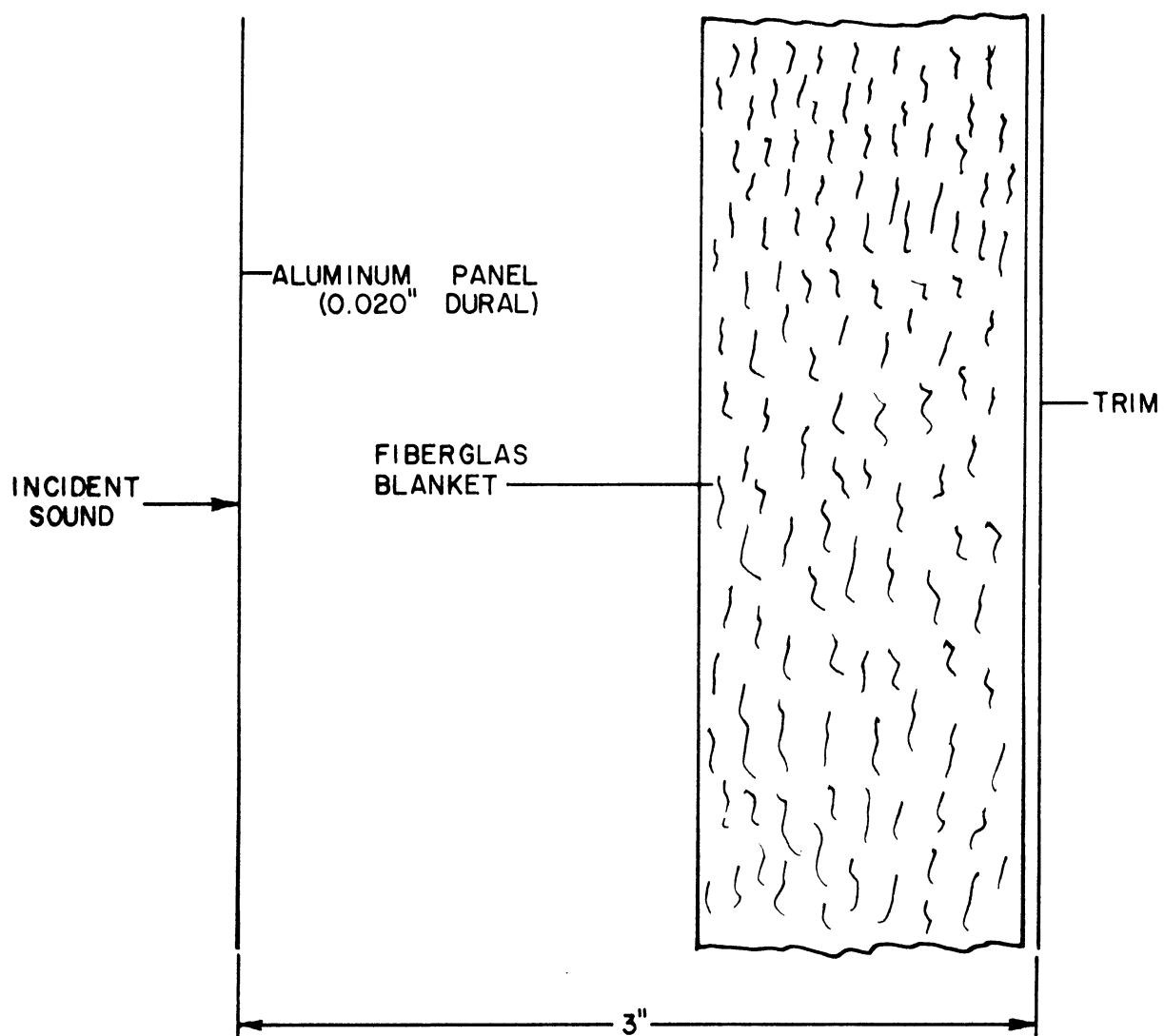


Fig. 2. Typical test configuration for blanket-type samples.

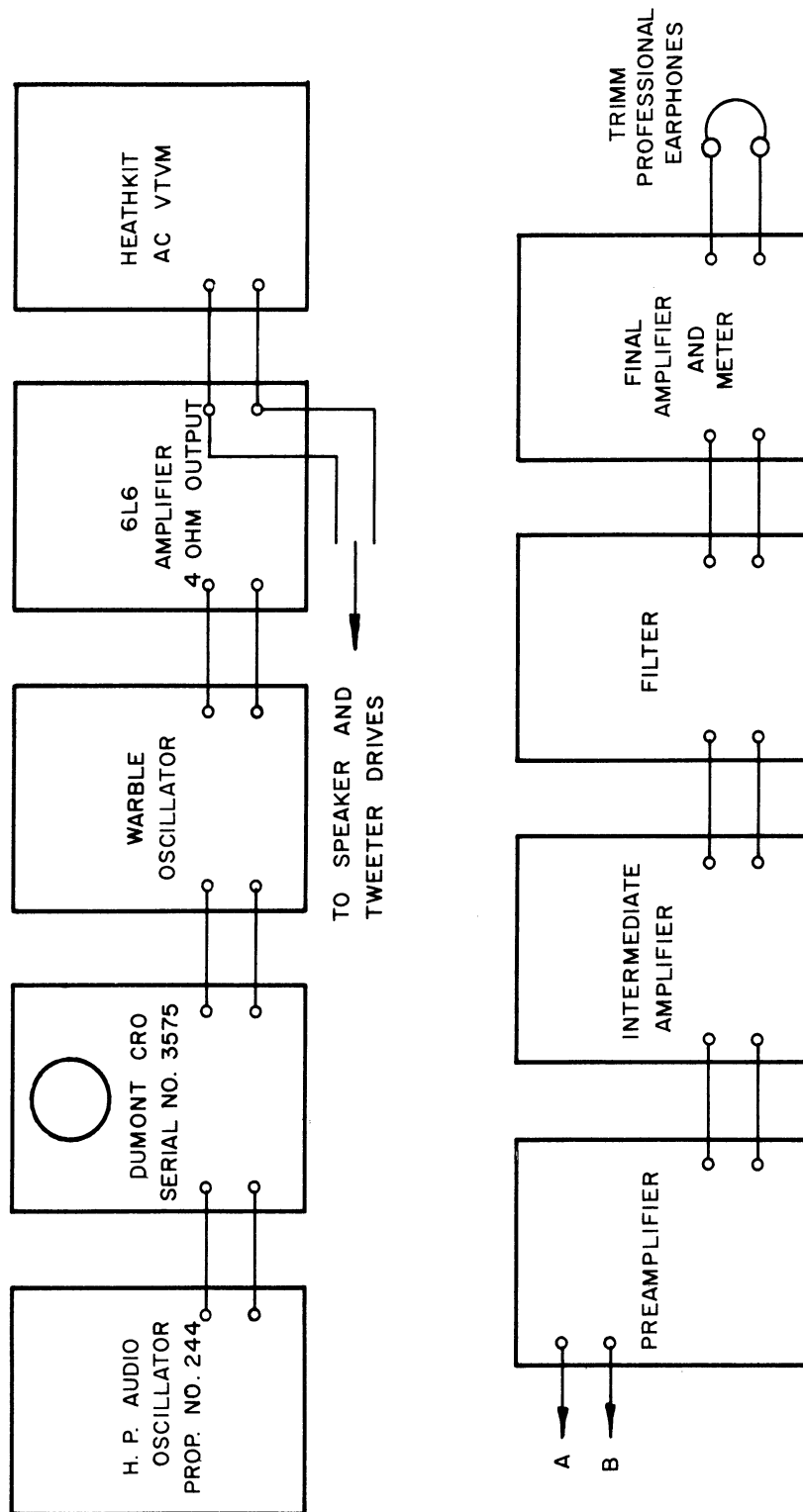


Fig. 3. Instrumentation for small-sample aircraft-transmission-loss-test apparatus.

At higher frequencies, standing waves, volume resonances, etc., complicate the situation so that it is virtually impossible to ascertain the true nature of the acoustic signal driving the aluminum panel. At best, one can hope that whatever the acoustic situation at each frequency, it will repeat during each test.

In practice, the shape of the attenuation curve as a function of frequency for the aluminum panel is assumed known, particularly at frequencies well above its major resonances. The assumed attenuation is the so-called "weight law:

$$\text{Attenuation in db} = 20 \log_{10} \frac{\rho c}{\sqrt{\rho^2 c^2 + \omega^2 \sigma^2}}$$

where σ = surface density of the panel in g/sq cm,
 ω = circular natural frequency in radians per sec,
 ρ = density of air in g/cu cm,
 c = velocity of sound in air in cm/sec, and
 ρc = 42 rayls (dyne sec/cu cm) (Ref. 5).

For a nonresonant 0.020-in. aluminum panel, the formula yields the result shown in Fig. 4. The influence of the ρc -term in the denominator is apparent only below 150 cps in this case; in view of experimental inaccuracies, it is often neglected, and the curve in Fig. 4 is expressed as a straight line down to the lowest frequencies.

When the Small-Sample Aircraft-Transmission-Test Apparatus was originally activated, the positions of the two microphones were adjusted until the high-frequency portion of the attenuation curve for the bare aluminum panel resembled the theoretical weight-law curve. These microphone positions and other apparatus geometries were then held constant for all future testing. The difference between the theoretical attenuation curve for 0.020-in. aluminum and the experimentally observed attenuation was taken as the correction factor to be applied to other test data. Thus this correction factor implicitly included the behavior of the aluminum panel as well as the detailed acoustic behavior of the rest of the apparatus, microphone sensitivities, and instrument sensitivities. This correction factor must be rechecked at frequent intervals because it is extremely sensitive to the treatment of the aluminum panel. Replacing the aluminum panel, tightening the clamping bolts, or even pressing lightly on the installed panel are all likely to change the experimental values used to evaluate the correction factor.

From the preceding discussion, it is evident that the aluminum panel and the assumptions made about its behavior underlie the evaluation of all samples on the Small-Sample Aircraft-Transmission-Test Apparatus. The existing test method is satisfactory for ranking various combinations of lightweight flexible blankets and trim cloths in order of effectiveness; however, any treatment which influences the behavior of the standardized aluminum panel invalidates the method. Furthermore, any sample possessing appreciable stiffness will alter the experimental results in an unevaluable manner. For example, the results

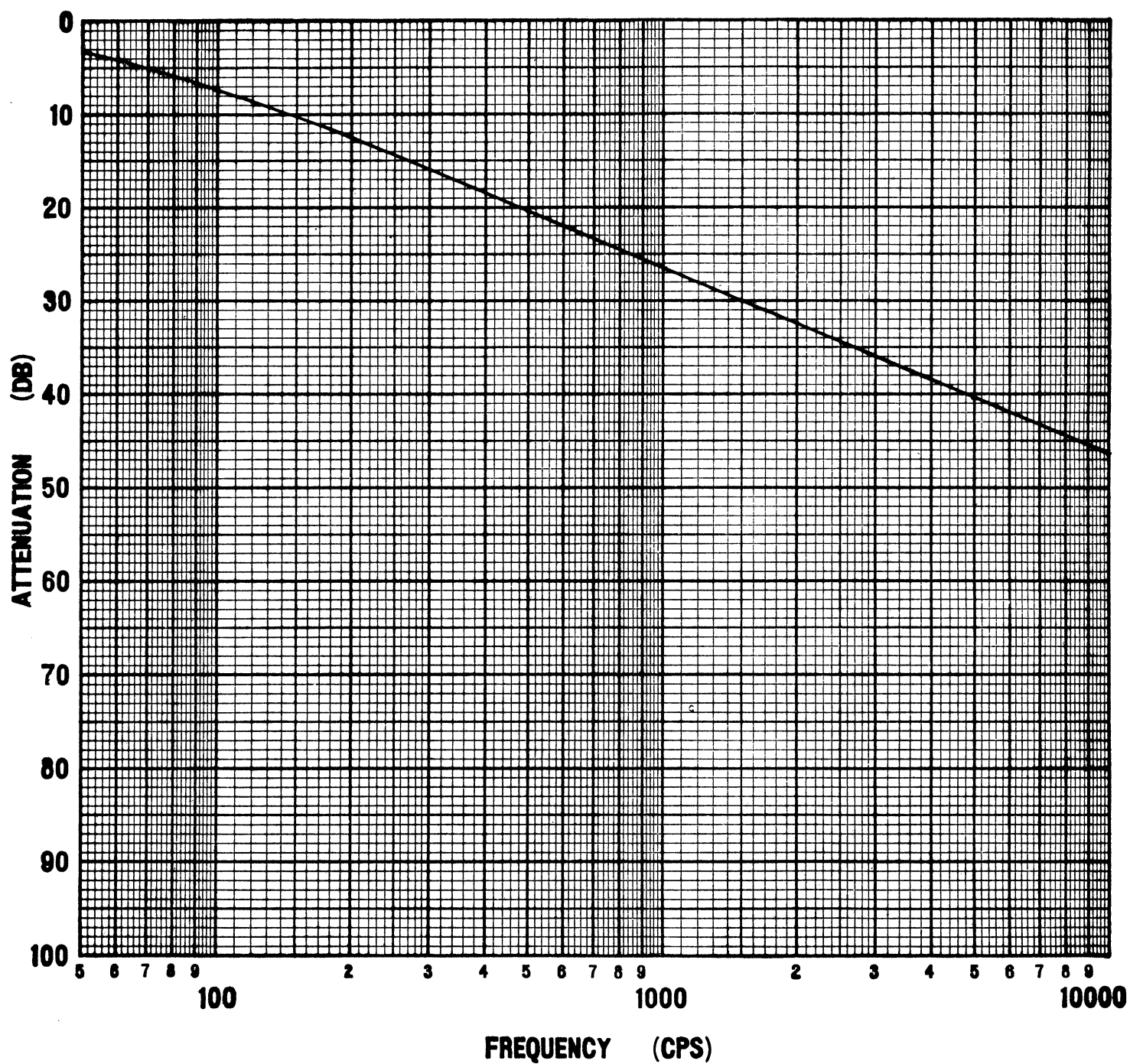


Fig. 4. "Weight law" for 0.020-in. aluminum panel.

obtained with a stiff honeycomb-type sample cannot be compared with those for blankets, and the honeycomb sample cannot be substituted for the aluminum panel because the transmission properties of the honeycomb are unknown. The difficulty arises when generalizing the specific test results in order to predict the acoustic behavior in a practical situation. (It is always possible to measure the transmission of any sample or configuration, but the results may apply only to that specific test situation.) Generally, whenever the stiffness of a transmission sample becomes a significant factor, the results are dependent upon the boundary (clamping) conditions.

The honeycomb-type samples supplied for test in July and August, 1957, can be characterized as very stiff in comparison to homogeneous panels of comparable weight. This has the effect, among others, of raising the natural frequencies which are scattered over a large portion of the measuring frequency range. The clamping of the sample then becomes a dominant factor affecting transmission. It seems unlikely that a honeycomb-type panel would be substituted for a blanket-type acoustic treatment; rather, this material would be used structurally with perhaps auxiliary acoustic treatments. Thus sample configurations other than those of the honeycomb in series with the 0.020-in. aluminum panel would appear more representative of the practical utilization.

The testing problem now has become one of evaluating the acoustic transmission through panels and treatments of diverse characteristics. This requires a more basic approach rather than the highly specialized approach represented by the Small-Sample Aircraft-Transmission-Test Apparatus. The previous advantages of small sample size and convenience may have to be sacrificed.

General methods for measuring acoustic transmission have been developed in the field of architectural acoustics. These have been reasonably satisfactory even in the case of walls having complex structure and capable of large attenuations. One of the most basic methods is the steady-state two-room technique in which the sample provides the communication between a reverberant source room and a reverberant receiving room. This method was used very early by W. C. Sabine and analyzed in detail by E. Buckingham (Ref. 6). The formula used in this method states that the

$$\text{Transmission loss in db} = L_1 - L_2 + 10 \log_{10} \left(\frac{S}{A} \right)$$

where L_1 = average sound-pressure level in the reverberant source room,

L_2 = average sound-pressure level in the reverberant receiving room,

S = area of the sample in sq ft, and

A = total absorption of the receiving room in sabins.

The assumption of diffuse sound fields in both the source and receiving rooms affects the derivation of the above equation in several ways. Diffuseness was assumed when writing the initial energy-balance equation and again

when replacing the acoustic energy-densities in both rooms by the average sound-pressure levels. Moreover, the diffuseness determines how any variation in panel transmission with angle of incidence and angle of reradiation will be integrated into a single value of transmission loss at each test frequency. From the practical standpoint, a diffuse source field is desirable since, a priori, all angles of incidence are likely to be encountered. Diffuseness on the receiving side is somewhat less fundamental but represents a convenient instrumental approach to evaluating the total acoustic energy traversing the panel. The two-reverberation-room method for measuring sound transmission through walls has been formalized in a recent ASA standard (Ref. 7). The measurements are usually at octave intervals using either a warble-tone source or bands of white noise.

Transmission measurements can be made using any acoustic source and receiving geometry but the corresponding analytic expressions have been worked out for only a few of the simpler geometries such as discussed above. The most informative measurement probably would involve a plane-wave source and the determination of both the directly transmitted plane-wave component and the scattered transmitted energy as a function of angle. This would have to be done for all possible angles of incidence at all frequencies. Such an approach involves a formidable amount of testing and could scarcely be used for the routine evaluation of samples.

The use of a diffuse source field although entailing a loss of detailed information, represents an enormous simplification. An anechoic chamber can be used on the receiving side of the panel. Detection of any outstanding angular dependence of the transmission (minor variations will be masked because of the diffuse source) can be accomplished at the expense of additional labor since some survey of the transmitted sound field is required. The analytic analysis becomes cumbersome and it is difficult to evaluate the constant terms in the formula which permit expressing the attenuation in the absolute terms of transmission loss. The transmission-loss expression for a reverberant source room and an anechoic termination can have the general form

$$\text{Transmission loss in db} = L_1 - L_a + K$$

- where L_1 = average sound-pressure level in reverberant source room,
 L_a = "average" sound-pressure level taken in anechoic termination, and
 K = constant (involving various parameters fixed by the test apparatus and usually frequency dependent).

If the constant K is not evaluated explicitly, a more suitable expression would be

$$\text{Attenuation in db} = L_1 - L_a.$$

The test arrangement selected for evaluating aircraft samples of diverse characteristics is the one involving a reverberant source room and an anechoic termination. This selection is based on several major considerations.

1. It meets the objections to the use of the Small-Sample Aircraft-Transmission-Test Apparatus.
2. It permits detecting unusual angular variations of transmission in complex samples.
3. Close-in surveys of panels (in their resonant ranges) can be accomplished more accurately than in a reverberant termination.
4. The anechoic termination could be more conveniently and more economically provided in the existing building facility.

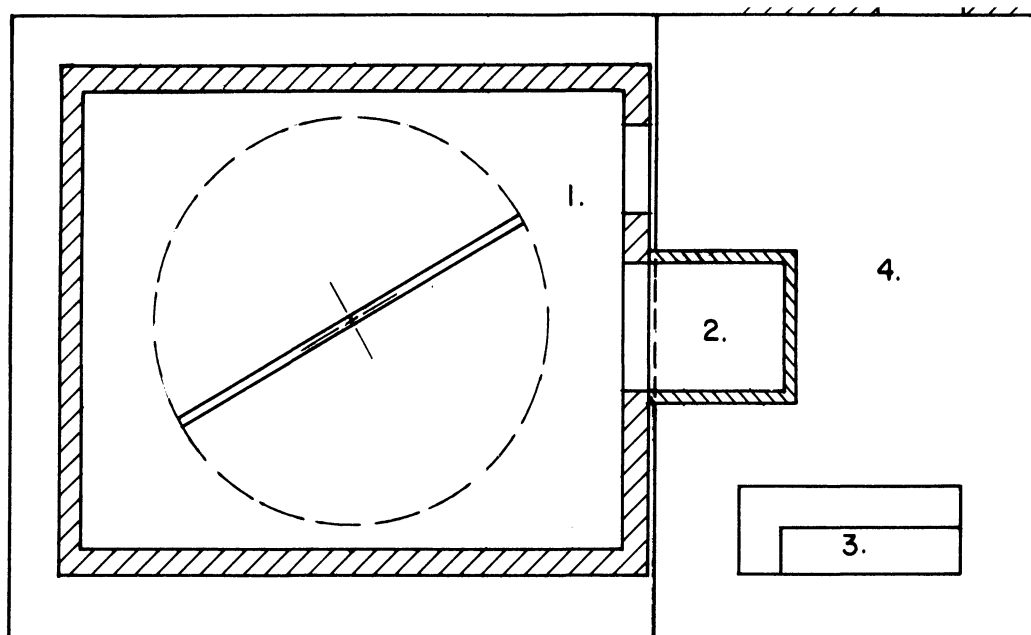
The disadvantages of this method are the difficulty in absolute evaluation and the necessity for a survey of the acoustic field in the anechoic termination. However, absolute measurements by the two-reverberation-room method can be conducted in the Michigan facility although only with the considerable inconvenience of using the control room as the second reverberation room (see Fig. 5). Nevertheless, absolute values can be obtained for some panels and K can be evaluated empirically. The necessity of a microphone survey in the anechoic termination merely involves additional labor and as a consequence yields additional important information about the sample.

The remainder of this report discusses the reverberant-source anechoic-termination facility and some of the experiments performed with it in considerable detail. One should carefully distinguish the potentialities of the method of measurement from the particular experiments which were conducted and reported below. In order to provide a possibility for comparison with previous tests, and because the honeycomb samples on hand did not permit exploiting the much larger transmission window available, all tests were conducted with 17.5-in.-square samples. The results of these tests largely corroborate the need for a new test method. Moreover, the use of such a small sample abnormally accentuated various measurement problems and provided an exacting background against which to develop instrumentation and methodology.

3.2 DESCRIPTION OF FACILITIES

3.2.1 The Reverberation Room

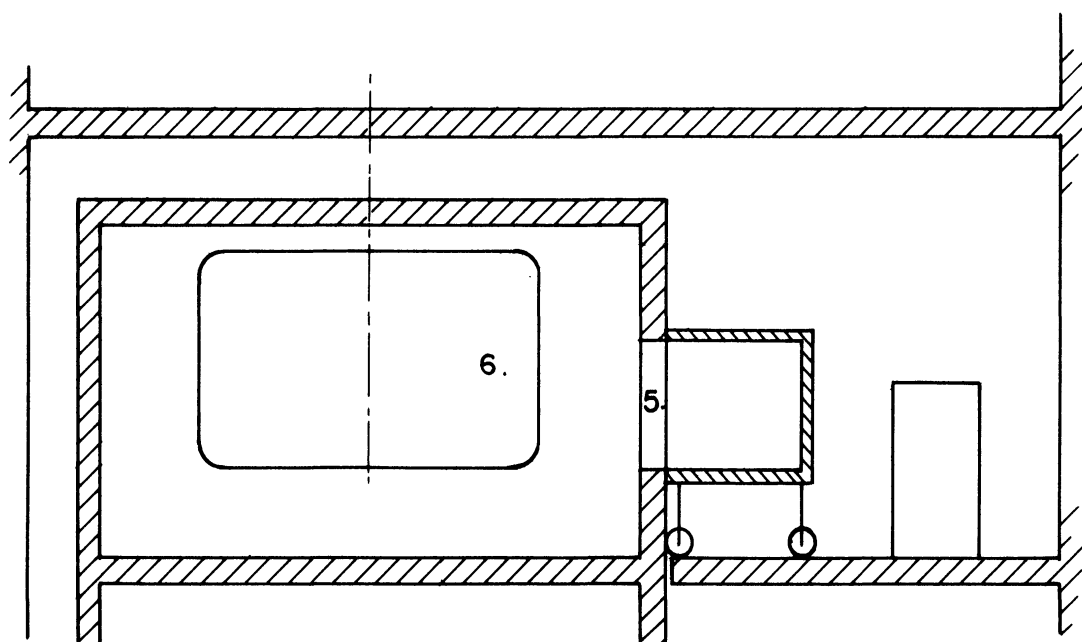
The reverberation room is a rectangular enclosure structurally isolated from the surrounding building and constructed of 1-ft-thick reinforced concrete walls. It is 22 ft long by 18 ft wide by 13 ft, 10 in. high as shown in plan and vertical section in Fig. 5. The interior surfaces are finished with specially hard acoustically reflecting plaster to maximize reverberation. A 5-ft-



PLAN

LEGEND

- | | |
|-------------------------|-------------------|
| 1. REVERBERATION ROOM | 4. CONTROL ROOM |
| 2. ANECHOIC TERMINATION | 5. WINDOW |
| 3. CONTROL CONSOLE | 6. REFLECTOR VANE |



ELEVATION

SCALE: $1/8" = 1'-0"$

Fig. 5. Reverberation-room test facility.

square window for transmission measurements communicates with the adjacent control room. Double steel covers seal this window when it is not in use. Double steel doors provide access from the control room and a special conduit accommodates electrical signal leads.

An aluminum reflector vane, 16 ft, 3 in. wide by 8 ft, 5 in. high, is suspended on a shaft through an acoustical seal located at the center of the ceiling. The vane can be rotated at 12 rpm by a quiet drive mechanism located outside of the reverberation room. Two General Electric model S-1201-A loudspeakers, each rated at 25 watts, are permanently mounted on the reflector vane for use as acoustic sources. Provision has been made also for supporting two microphones and their preamplifiers on the reflector vane if desired.

3.2.2 The Anechoic Termination

The absorptive or anechoic termination is a movable, 6-ft cubical box constructed from 3/4-in. plywood and open on one end to match the transmission window in the reverberation room. The four sides of this box are lined with a composite fiberglass blanket 6 in. thick and designed to provide large acoustic absorption over an extended frequency range. The rear of the termination box is covered with fiberglass wedges likewise designed for high absorptivity over an extended frequency range. Moreover, the wedge shape scatters any residual acoustic reflection instead of sending it directly back. An isolating rubber seal surrounds the open face of the termination and minimizes structure-borne sound communication between the reverberation room and this anechoic termination. Figure 6 illustrates the general features of the anechoic termination.

3.2.3 Transmission Window

As mentioned above, the transmission window is a square opening of 5-ft interior dimensions in the reverberation-room wall. It is framed with 12-in. 30-lb steel channel. Stud bolts around the frame provide for attaching steel cover plates on both sides and for attaching samples if desired.

Full-size samples are frequently placed within the window and sealed around the edges with modeling clay. For smaller samples, usually a suitable massive wooden adapter frame is sealed into the window and the sample mounted into the adapter in some appropriate manner. The wooden adapter used in some of the current experiments is illustrated in Fig. 7.

3.2.4 The Electronic Instrumentation

The majority of the control and measurement instruments associated with the reverberation room is located in the adjacent control room (see Fig. 5). This instrumentation is organized in a control console. (See Fig. 8. This figure was reproduced from a planning sketch and represents the instrument facilities

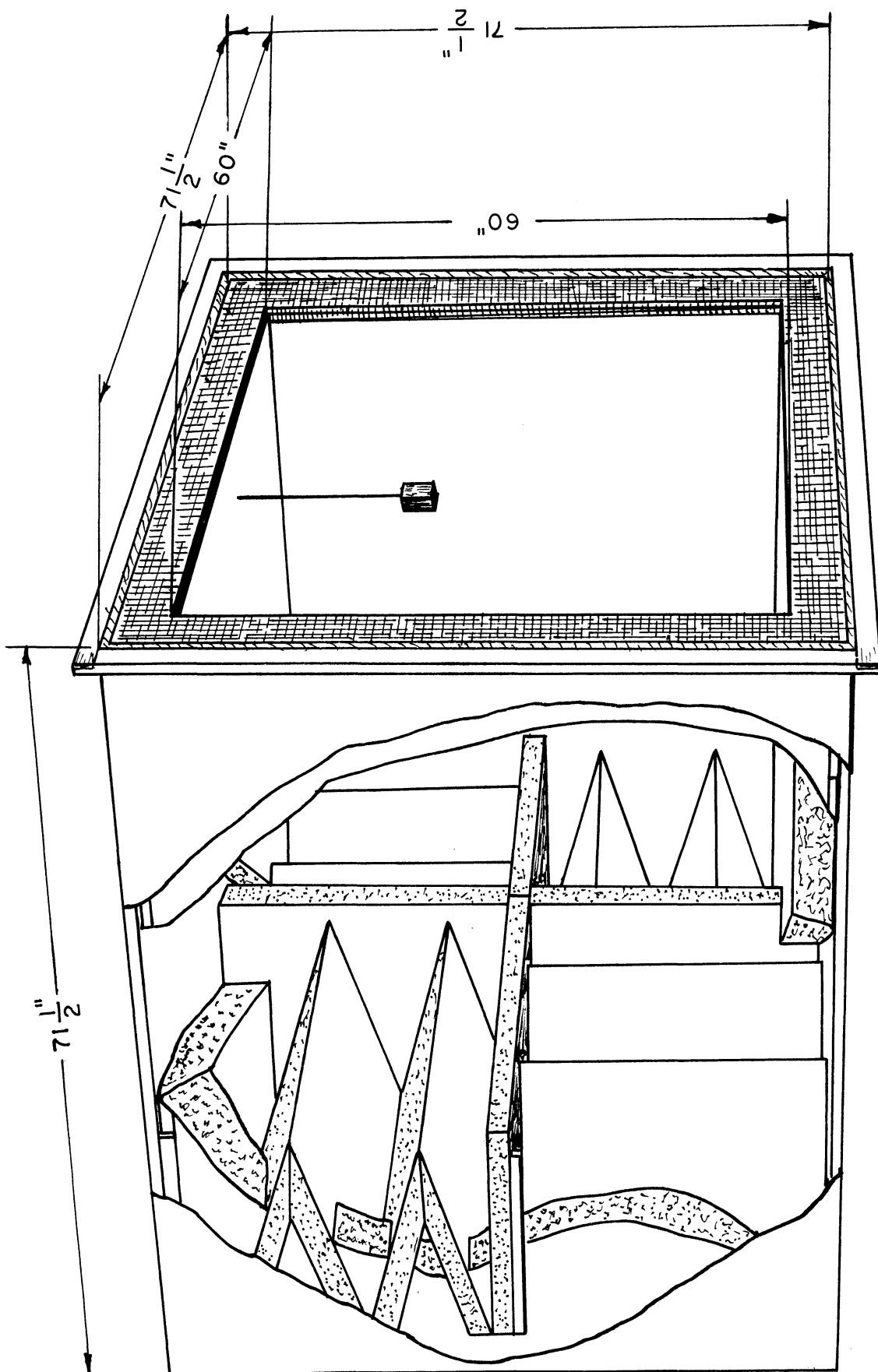


Fig. 6. Schematic of anechoic termination.

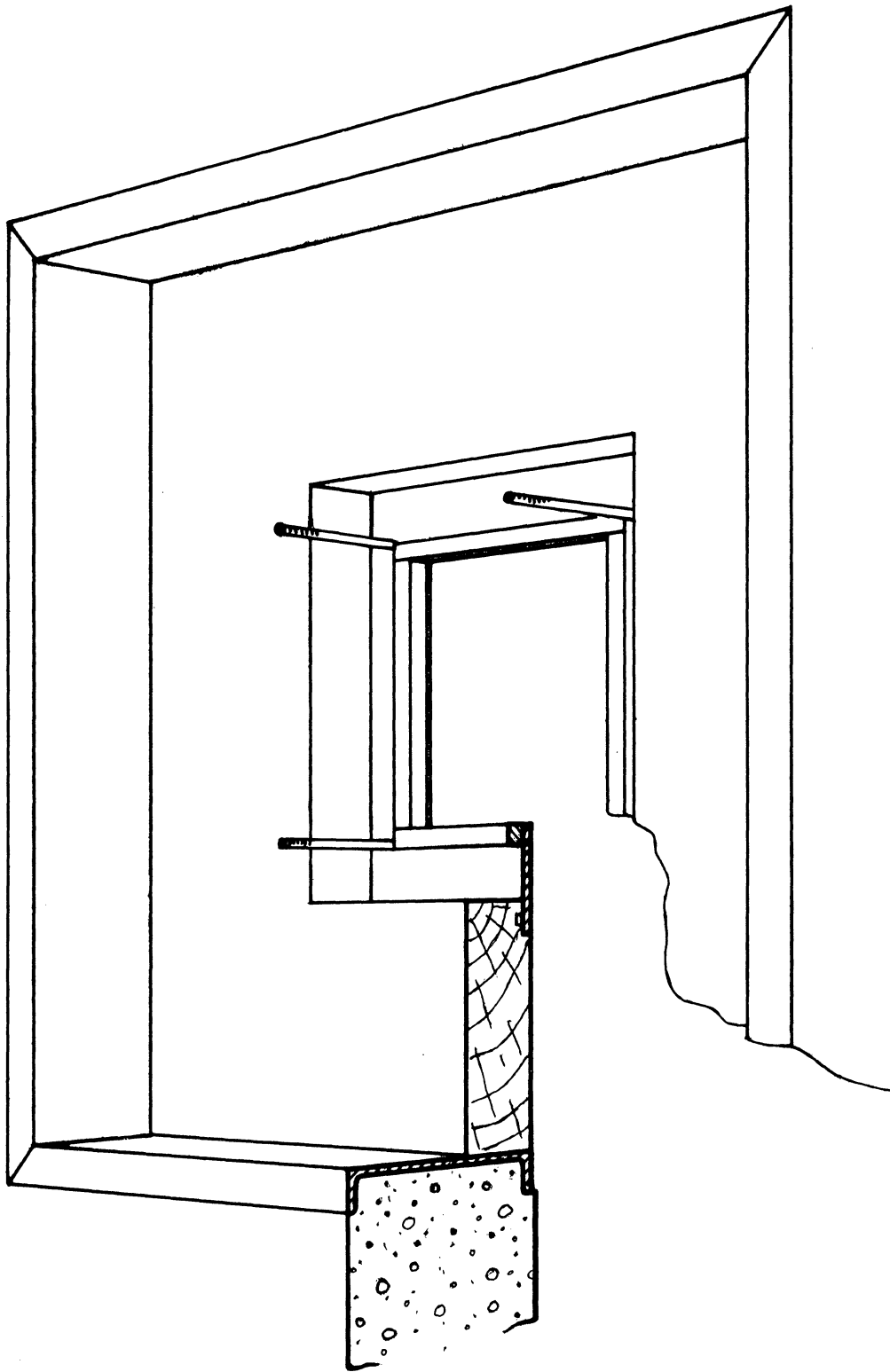


Fig. 7. Cutaway of transmission window, adapter, and sample holder.

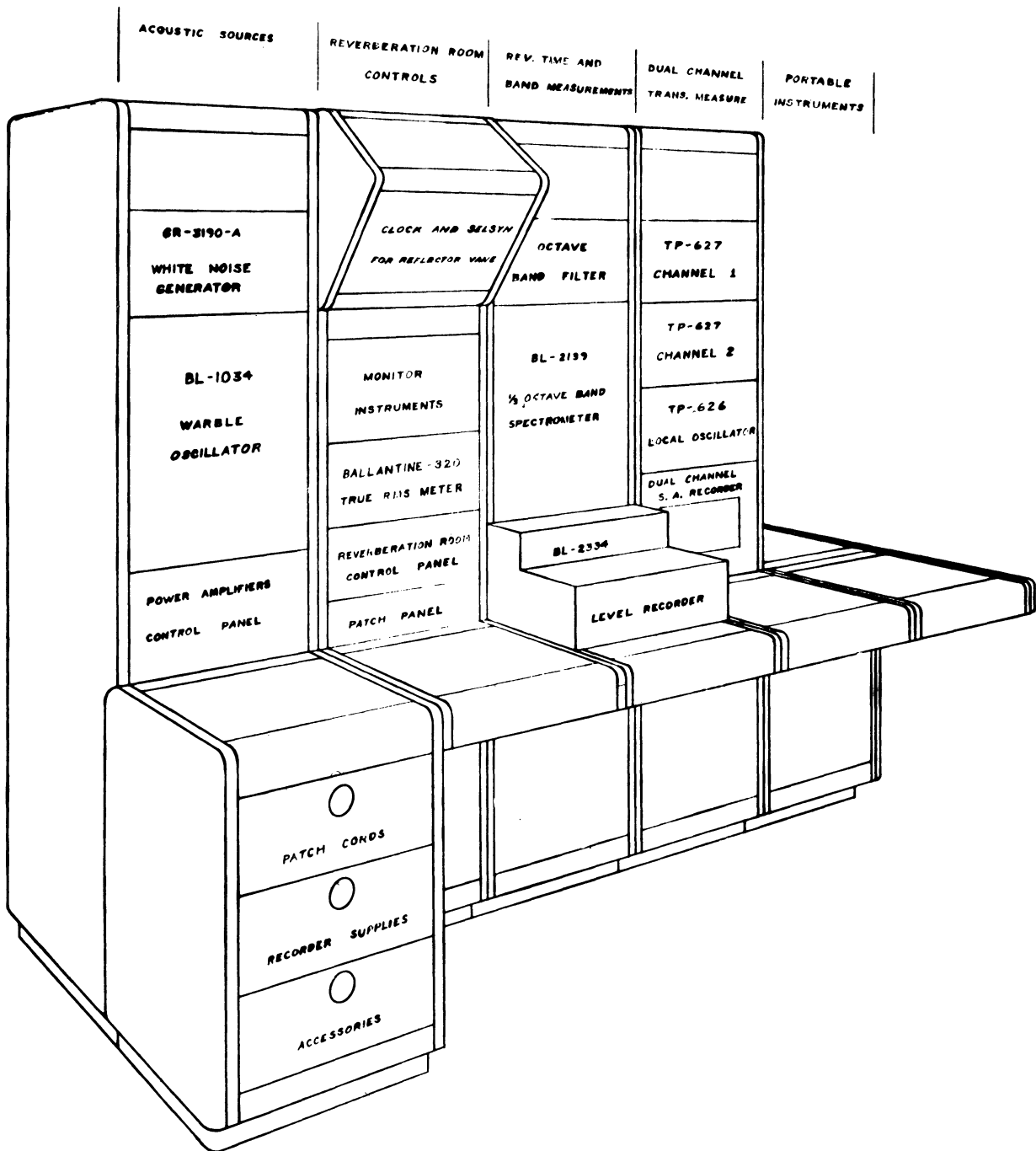


Fig. 8. Sketch of control console.

being provided by The University of Michigan. Not all the instruments noted are available yet.) The console provides easy access to all instruments, and permits convenient interconnection of instruments and the monitoring of signals at every point. Two acoustic sources are available: A General Radio Corporation Random Noise Generator Type 1390-A and a Bruel and Kjaer Beat Frequency Oscillator Type 1014 capable of pure or warble tones from 20 to 20,000 cps. The above signals can be fed to two McIntosh Model MC-30, 30-watt power amplifiers wired for 600-ohm line output. The input and output signals pass through monitor and control strips and can be switched to the loudspeakers mounted on the reflector vane or to any other selected acoustic transducer.

The analyzing circuitry includes Altec Type 633-A microphones, microphone transformers, and Tektronik Type 122 Low-Level Preamplifiers which can be placed either on the rotating reflector vane or at stationary locations exterior to the reverberation room. The preamplifier output signals appear on a terminal strip on the control console. From there, they may be connected at will to a Ballantine Model 320 True Root-Mean-Square Voltmeter, a Bruel and Kjaer Type 2304 Level Recorder or a modified dual-channel Sound Apparatus Company Model RZ recorder equipped with 40-db potentiometers. For transmission experiments, the Model RZ recorder has been modified to yield a d-c analog voltage proportional to the difference of the logarithms of the input signals. This analog voltage is usually recorded on a portable Brown (Minneapolis-Honeywell Regulator Company) Model C153X17(VA)-X-30(K-1), CB 1043, variable-span strip-chart recorder. Other instruments such as oscilloscopes, filters, and special attenuators are added to the instrument chains as necessary.

3.3 ACOUSTICAL AND ELECTRICAL CHARACTERISTICS OF FACILITY

The instrumentation mounted in the control console, as described in the preceding section, was new and was used for the first time to carry out the research reported here. Consequently, it was essential to check the instrumentation thoroughly and also to investigate experimentally the acoustic characteristics of the reverberation room and the anechoic termination preliminary to initiating transmission measurements. However, in conformance with the budget limitations of the present contract, these investigations were minimized as much as technically feasible.

3.3.1 Instrumentation

Both the source and analysis instrumentation were investigated to determine the maximum electrical noise levels resulting from individual instruments and combinations thereof. Careful checks were made in certain cases where long leads or critical contacts, such as the slipring assembly on the reflector vane, might result in pickup or feedover problems. Indeed, it was discovered that several interconnections led to excellent reception of commercial radio stations located some 50 miles distant. The various types of interference were eliminated

by careful interconnection of instruments, avoidance of ground loops, and, in a few situations, by filtering. Tests were also made for microphonic noise induced by high acoustic levels on such instruments as preamplifiers.

The residual noise levels were very low and inherent to the individual instruments involved. As a consequence, very low-level acoustic signals could be handled without interference from instrument noise. Because the actual measurements obtained during these investigations are of value only to this particular laboratory, they will not be presented in detail. However, a typical ambient wide-band acoustic noise level taken in the reverberation room with an Altec type 633-A microphone and with the reflector vane rotating amounted to some 50 db. The major portion of this acoustic signal occurred at low frequencies and originated primarily from various pumps, an elevator mechanism, and general activity in the building as well as from traffic on the nearby road. Also included in this 50-db level were a single 117-cps tone resulting from the rotating vane and the windage noise generated by the vane motion.

3.3.2 Acoustical Behavior in the Reverberation Room

A reverberation room is employed in acoustical experiments because, subject to certain restrictions mentioned below, the acoustical energy present in such a room is diffuse. Thus, any small test surface placed within the room will be bombarded with sound equally from all directions and the room walls themselves will be bombarded from all possible directions within the room. Furthermore, a diffuse sound field also implies certain simple and specific relationships among sound pressure, sound intensity, and energy density.

The exact mathematical analysis of both the steady-state and transient acoustical behavior of a room or enclosure has been accomplished only for a few simple wall geometries. Of these, the rectangular room has been treated extensively (Ref. 8). This rectangular room analysis, of course, is applicable to the reverberation room employed in the present sound-transmission experiments.

The referenced analysis shows that diffuse behavior can be expected in a rectangular room, except for a small region in the immediate vicinity of the source, if the room walls are reasonably nonabsorbing and if the frequency is high enough to excite simultaneously a multiplicity of natural room modes. The University's reverberation room has walls of very low absorptivity as corroborated by the lengthy reverberation times listed in Table I (page 11).

Morse's analysis (Ref. 8) describes a minimum frequency, ν_{\min} , above which a rectangular reverberation room will exhibit fairly uniform response in frequency and in distribution over the volume of the room. Below this frequency, the normal room modes are too widely separated for diffusion. The mathematical expression of ν_{\min} is

$$\nu_{\min} \simeq \frac{10^4 / \sqrt{V}}{\sqrt{\Delta \nu + (4/T)}}$$

TABLE I
REVERBERATION TIME, $T^{(a)}$

Frequency (cps)	T for Bare Room ^(b) (seconds)	T for Open Transmission Window ^(c) (seconds)
125	11.5	5.5
250	12.3	5.8
500	10.0	5.8
1000	8.3	5.0
2000	5.9	3.7
4000	3.1	2.1
8000	1.2	1.0

- (a) T = time in seconds for the sound pressure to fall to 0.001 of its original amplitude. These values represent the general magnitude of the reverberation time but are probably not precise due to some trouble with the warble oscillator discovered and corrected subsequently.
- (b) Tests conducted with a warble-tone source and an empty reverberation room. The transmission window was covered with two 3/16-in.-thick steel cover plates, one on each side of the wall.
- (c) Tests conducted in a similar manner to (b) except that the transmission window contained a wooden adapter frame permitting a 28-in. square opening into the anechoic-termination chamber.
-

where V = room volume in cu ft,
 T = reverberation time in sec,
 ν = frequency in cps, and,
 $\Delta\nu$ = source bandwidth in cps.

For the University's reverberation room, $V = 5350$ cu ft, $T = 10$ sec and $\Delta\nu = 0$ if pure-tone excitation is used. Substitution of these values into the above equation yields

$$\nu_{\min} \simeq 216 \text{ cps} .$$

This theoretical value of a minimum frequency for diffuse behavior agrees well with experimental observations. Since it is desirable in many acoustical experiments, and the present transmission experiments in particular, to extend the useful frequency range down to 100 cps or lower, various means of effecting low-frequency diffusion in the reverberation room were investigated experimentally.

Diffusion, in the present case, is considered to exist if the same sound pressure as a function of frequency is measured at widely separated points in

the reverberation room. The instrumentation shown in Fig. 9 was used for these experiments except that both microphones were located in the reverberation room as shown in Fig. 10. Attention was restricted to the frequency range of from 50 to 200 cps which was swept logarithmically from the lower to the upper frequency limit in approximately 20 min. The sound pressures at the two microphones were recorded on the A and B channels of the Sound Apparatus Recorder. These two graphs of sound pressure versus time (i.e., frequency) can show considerable variation due to the behavior of the loudspeaker source. However, if diffusion exists, the two traces ought to fluctuate in synchronism and the ratio of the two sound pressures graphed by the Brown recorder ought to be a straight line or, at worst, one which varies slowly and smoothly with frequency.

The reflector vane was rotating at 12 rpm during all experiments to assist in breaking up standing-wave patterns. Also, the Sound Apparatus Recorder had been altered so that its maximum rate of response was about 3 db/sec. These two factors tend to improve the diffusion at all frequencies as judged by the ratio of the two microphone signals. Nevertheless, a comparatively sudden increase occurred in the jaggedness of the ratio curve below about 200 cps for a pure-tone frequency sweep with a fixed location of the loudspeaker in the reverberation room.

Figure 11 presents as a function of frequency the ratio trace of the signals from two stationary microphones located as shown in Fig. 10 for four different sources. In two cases, a type AR-1 loudspeaker unit resting on the floor of the reverberation room and pointed upward and toward the corner of the room shown in Fig. 10 was used as the sound source. In the other two cases, one of the G. E. Type S-1201-A loudspeakers mounted on the moving reflector vane served as sound source. Each loudspeaker was supplied first with a pure-tone frequency sweep and then a warble-tone frequency sweep. The warble-tone condition consisted of modulating the oscillator signal in a linear-sawtooth manner at a rate of eight times per second by a nominal ± 20 cps from center frequency.

Figure 11 clearly shows, judging from the smoothness of the trace, that moving the source is very effective in extending diffusion to lower frequencies. Furthermore, it shows that by combining a warble-tone with a moving source, effective diffusion extends to a minimum frequency of perhaps 75 cps.

Ideally, the effects of varying warble width, warble rate and other parameters ought to be studied in detail to assure that optimum values have been chosen. A complete study of this sort is clearly beyond the scope of the present experiments. cursory investigations, however, indicated that the values reported above are near optimum and sufficiently noncritical to be satisfactory for routine measurements.

It is possible to mount the microphones and preamplifiers on the rotating reflector vane if desired. An investigation of low-frequency diffusion, similar to that described above, was carried out with one microphone stationary and the other microphone moving with the reflector vane. The results were almost

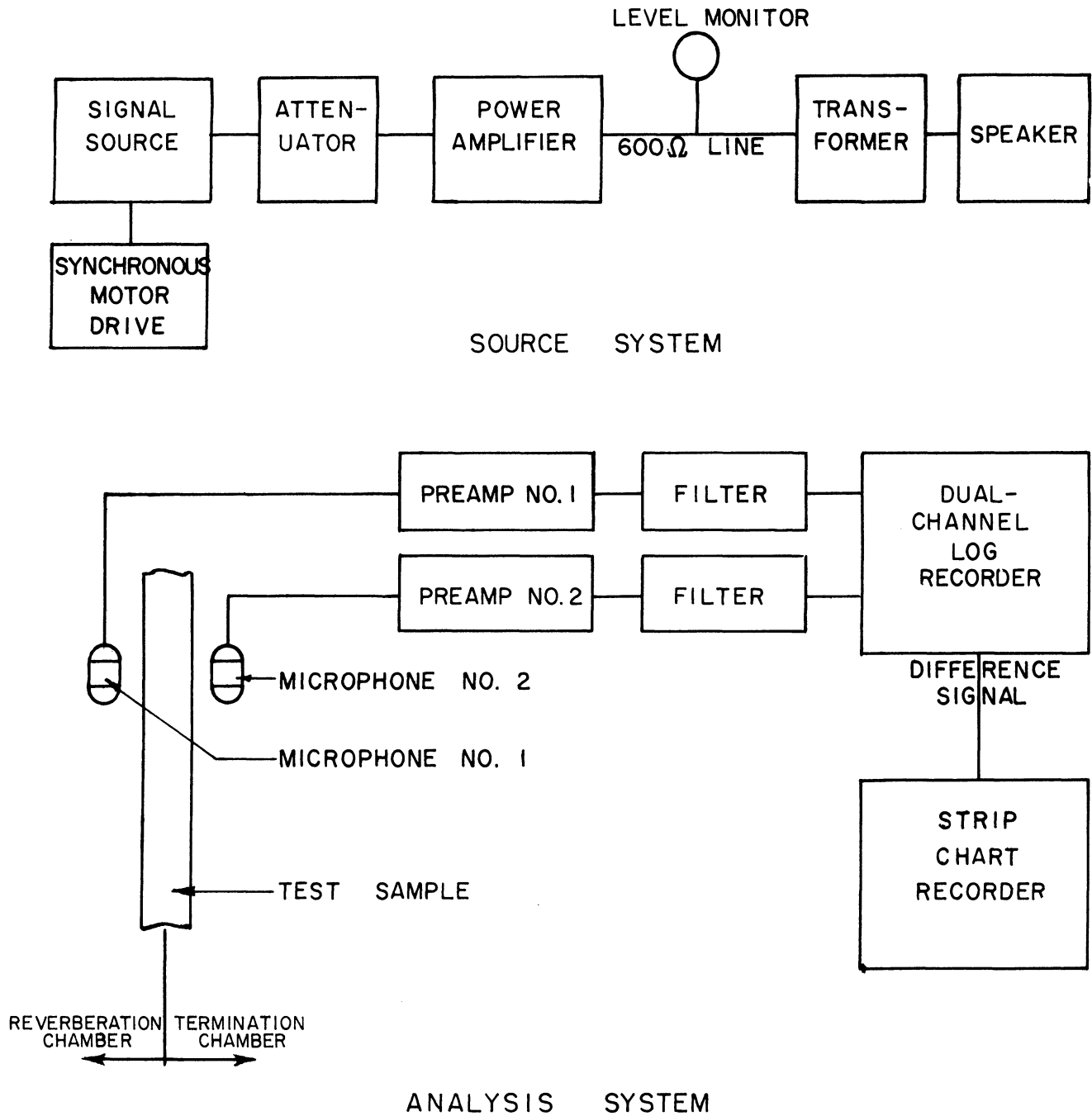
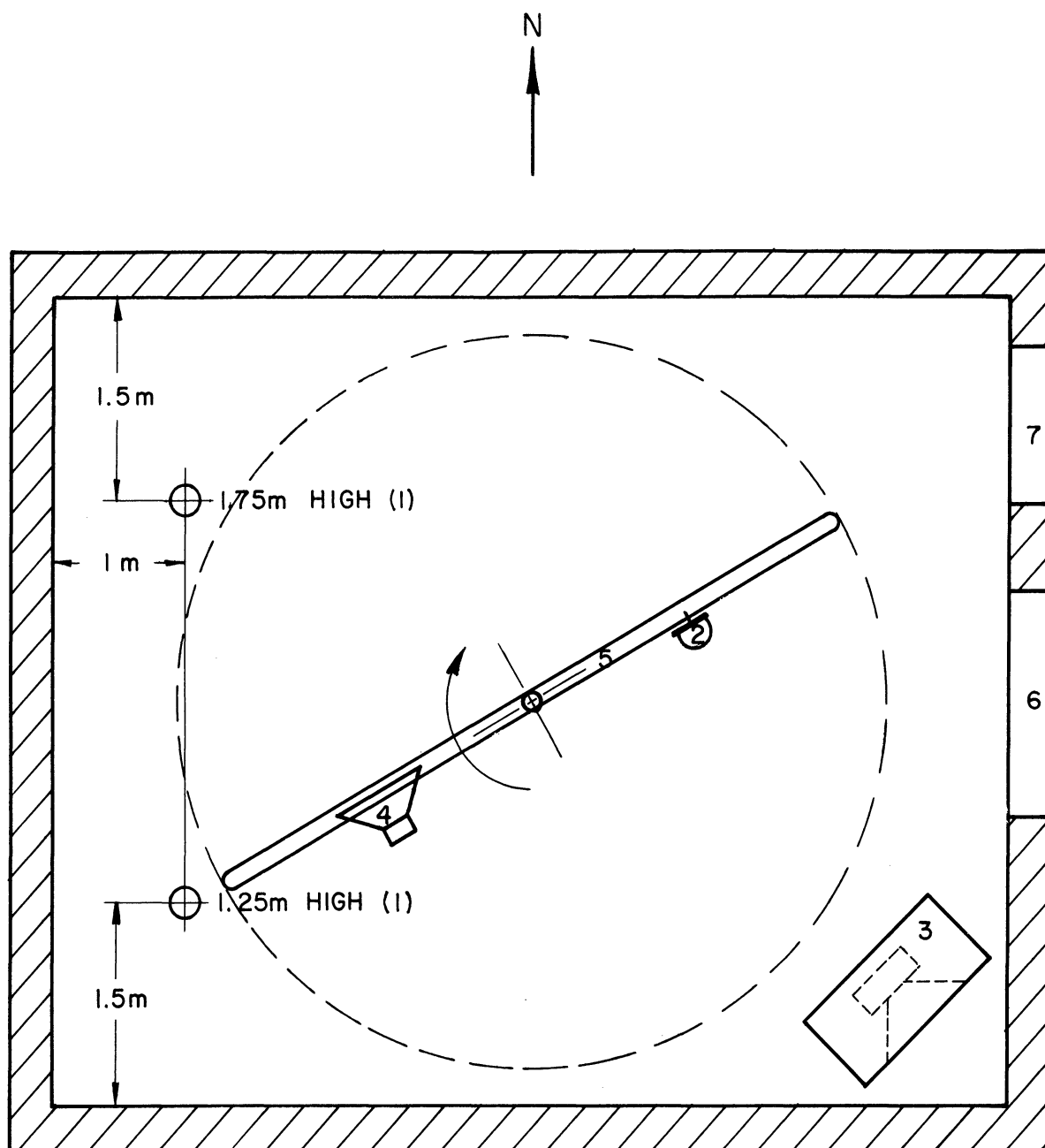


Fig. 9. Instrumentation for transmission experiments.



LEGEND

- | | |
|--------------------------|------------------------|
| 1. STATIONARY MICROPHONE | 5. REFLECTOR VANE |
| 2. MOVING MICROPHONE | 6. TRANSMISSION WINDOW |
| 3. STATIONARY SPEAKER | 7. DOOR |
| 4. MOVING SPEAKER | |

Fig. 10. Location of microphones and sources in reverberation room.

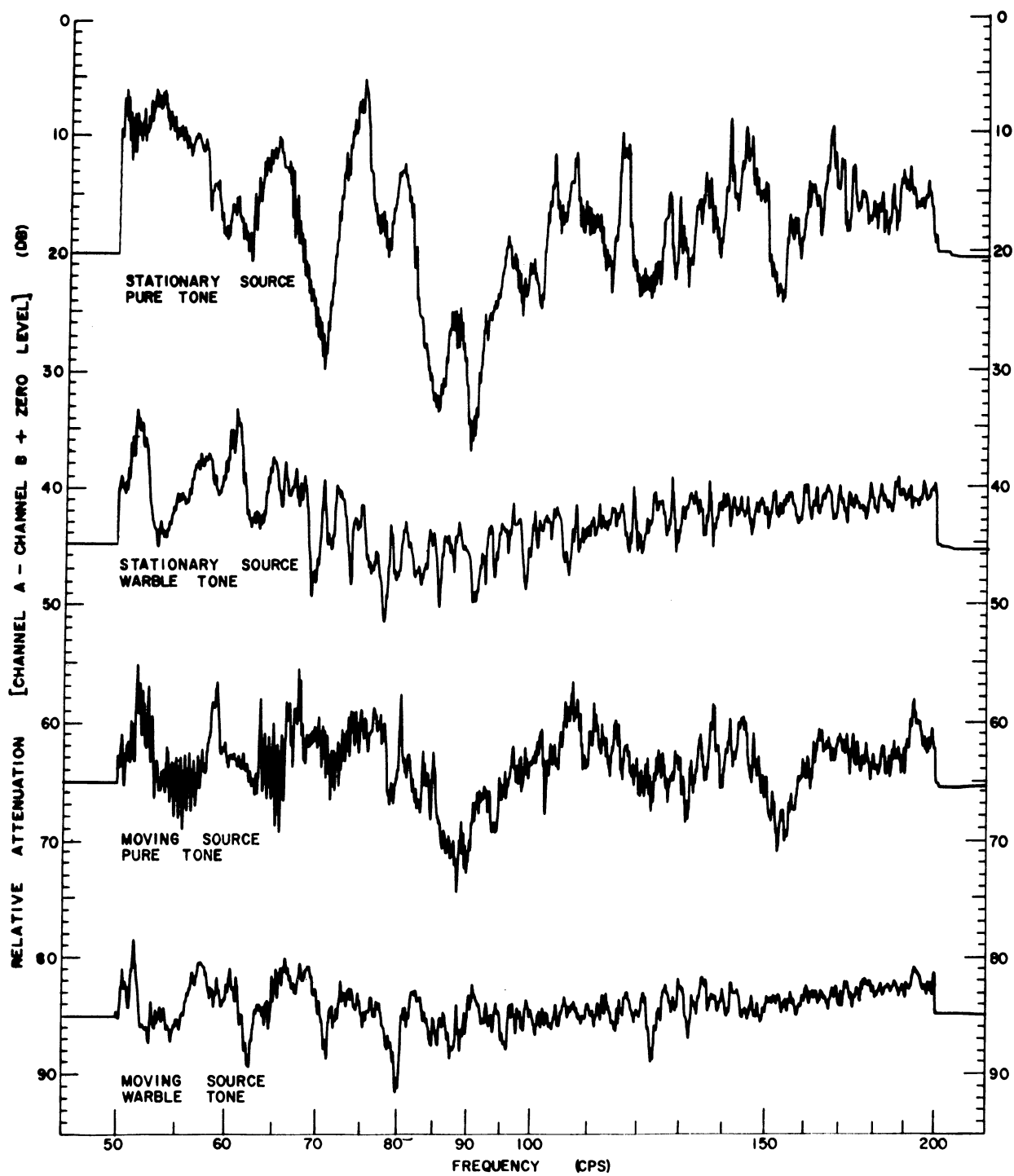


Fig. 11. Results of diffusion experiment.

identical to those shown in Fig. 11 and hence are not repeated here.

A supplementary set of transmission experiments in the 50- to 200-cps frequency range were performed using fixed or moving sources, pure-tone or warble-tone frequency sweeps, and a stationary or a moving microphone in the reverberation room. The microphone in the termination chamber was stationary and at its usual central location. The transmission sample used was 17.5 in. square and consisted of the 0.020-in. aluminum panel followed by a 2-in. air space, a 1-in.-thick aluminum-faced honeycomb and a trim cloth. As in the case of the reverberation-room diffusion experiments, a moving, warble-tone source was most effective in eliminating low-frequency standing-wave troubles, and moving the reverberation-room microphone had negligible effect.

On the basis of the studies reported in this section and general considerations, it was decided tentatively to conduct transmission measurements with the following conditions:

1. Use a stationary microphone in the reverberation room located somewhere near the transmission window.
2. Use one of the vane-mounted speakers as the moving source. (Parallel operation of both vane-mounted speakers was not satisfactory.)
3. Use a ± 20 -cps nominal frequency warble at a warble rate of eight times per second.
4. Maintain the warble width and rate constant with increasing frequency because higher-frequency diffusion is inherently adequate.

3.3.3 Acoustic Behavior in the Anechoic Termination

The primary aims in the investigation of the acoustic behavior here were to determine the significance of diffraction due to a finite window size and the directional effects which might arise due to the vibrational behavior of the sample. Also of interest were the effectiveness of the absorptive lining of the termination chamber and possible interferences at low frequencies from standing waves in the control room resulting from leakage transmission through the termination's walls.

Three separate types of exploratory tests were conducted, utilizing in each case the 17.5-in.-square 0.020-in. aluminum panel adapted from the Small-Sample Aircraft-Transmission-Test Apparatus (see Fig. 7.) Thus, the aluminum panel became the effective acoustic source radiating into the anechoic termination. The primary acoustic signal was generated by a pure-tone signal applied to the stationary AR-1 loudspeaker located in the reverberation room as illustrated in Fig. 10, and the reflector vane was always operated at 12 rpm.

The initial experiment was designed to uncover gross variations in sound-pressure level both with respect to microphone location and frequency. A frequency range of from 300 to 500 cps was selected for investigation because:

1. it was as low as would assure diffusion in the reverberation room for a pure-tone signal;
2. the absorptive treatment of the anechoic termination was expected to be effective, thereby eliminating standing-wave patterns caused by multiple reflections within the termination; and
3. any directional patterns from the transmission window and sample would likely be well-formed but not excessively complex.

The experiment consisted of five transmission measurements over this frequency range employing the instrumentation shown in Fig. 9. The microphone in the reverberation room rotated with the reflector vane (see Fig. 10, position no. 2) while the microphone in the anechoic termination was located successively at the five positions indicated at the top of Fig. 12. The resulting attenuations are displayed at the bottom of Fig. 12. These curves show that the transmitted sound field is approximately symmetrical, the apparent magnitude reaching a maximum at the central microphone location. Since the frequency dependence is similar for all microphone positions, no pronounced diffraction or standing-wave phenomena were put in evidence. The use of the pure-tone signal enhanced the sensitivity of this test compared to the use of a warble-tone signal.

The finding of an amplitude maximum at the central microphone location in the above experiment suggested that another transmission experiment be performed. This time the microphone was traversed along a horizontal mid-height path parallel to and 3.5 ft distant from the sample for a range of 25 in. each side of center in 5-in. intervals. To limit the labor involved, this experiment was performed at three selected frequencies: 100, 400, and 4000 cps, the other test conditions remaining the same as in the previous experiment.

The results of this test are graphed in Fig. 13. Both the 4000-cps and the 400-cps curves appear smooth, rising to observable maxima of 2 db and 3.5 db, respectively, for central positions of the terminal microphone. The 100-cps curve exhibits an unsymmetrical shape, but this is of doubtful significance because source conditions were definitely not diffuse, and in any event, the variation is not large. The findings from this more detailed positional survey corroborate those of the first experiment and indicate that directional effects and standing-wave effects are comparatively small for a thin aluminum panel. Other tests have shown that the sound pressure decreases smoothly with increasing distance of the terminal microphone from the panel as would be expected in an anechoic termination.

A third experiment was performed to check critically the findings of the first two experiments in an independent manner. Both microphones were placed in the termination chamber 3.5 ft away from the transmission sample but other-

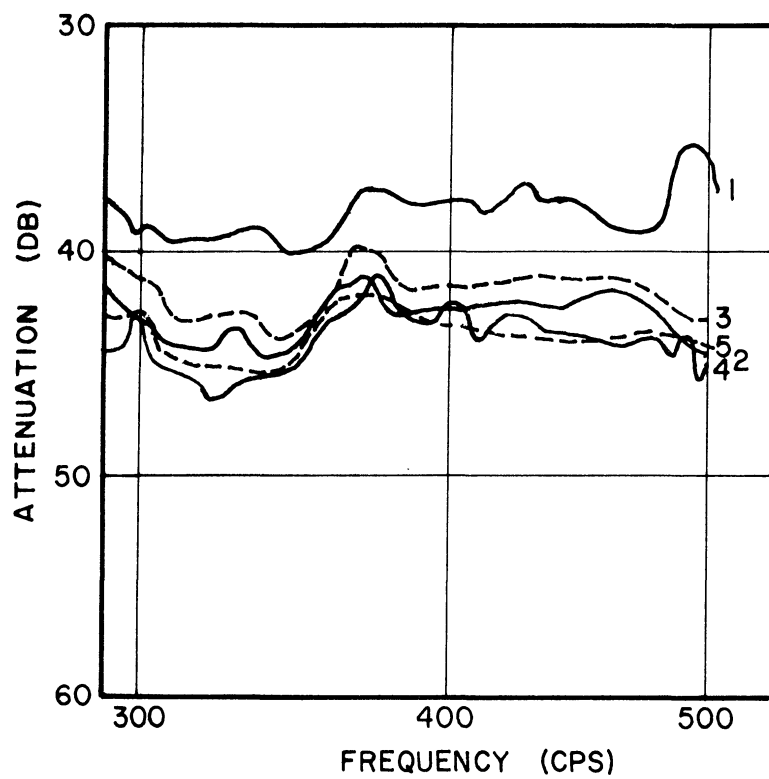
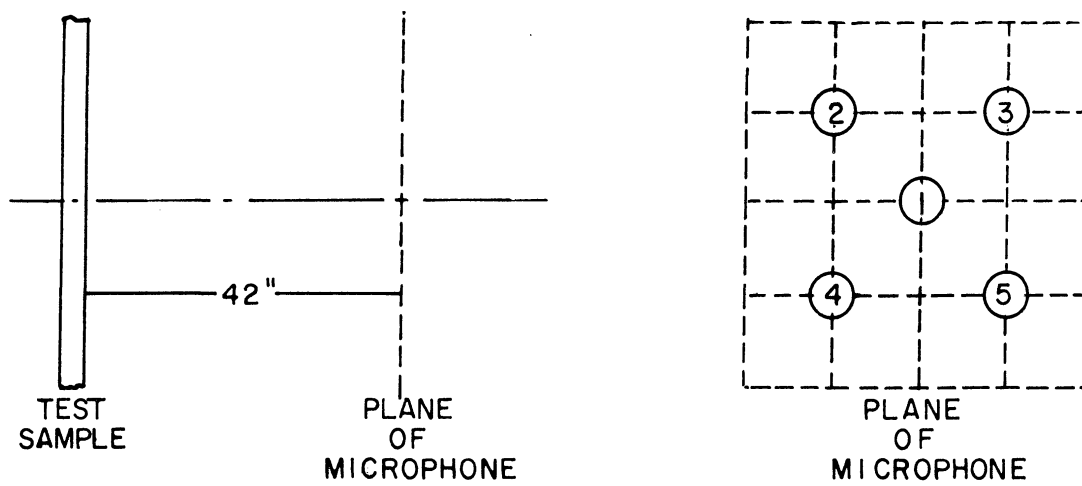


Fig. 12. Variation of attenuation with terminal microphone position.

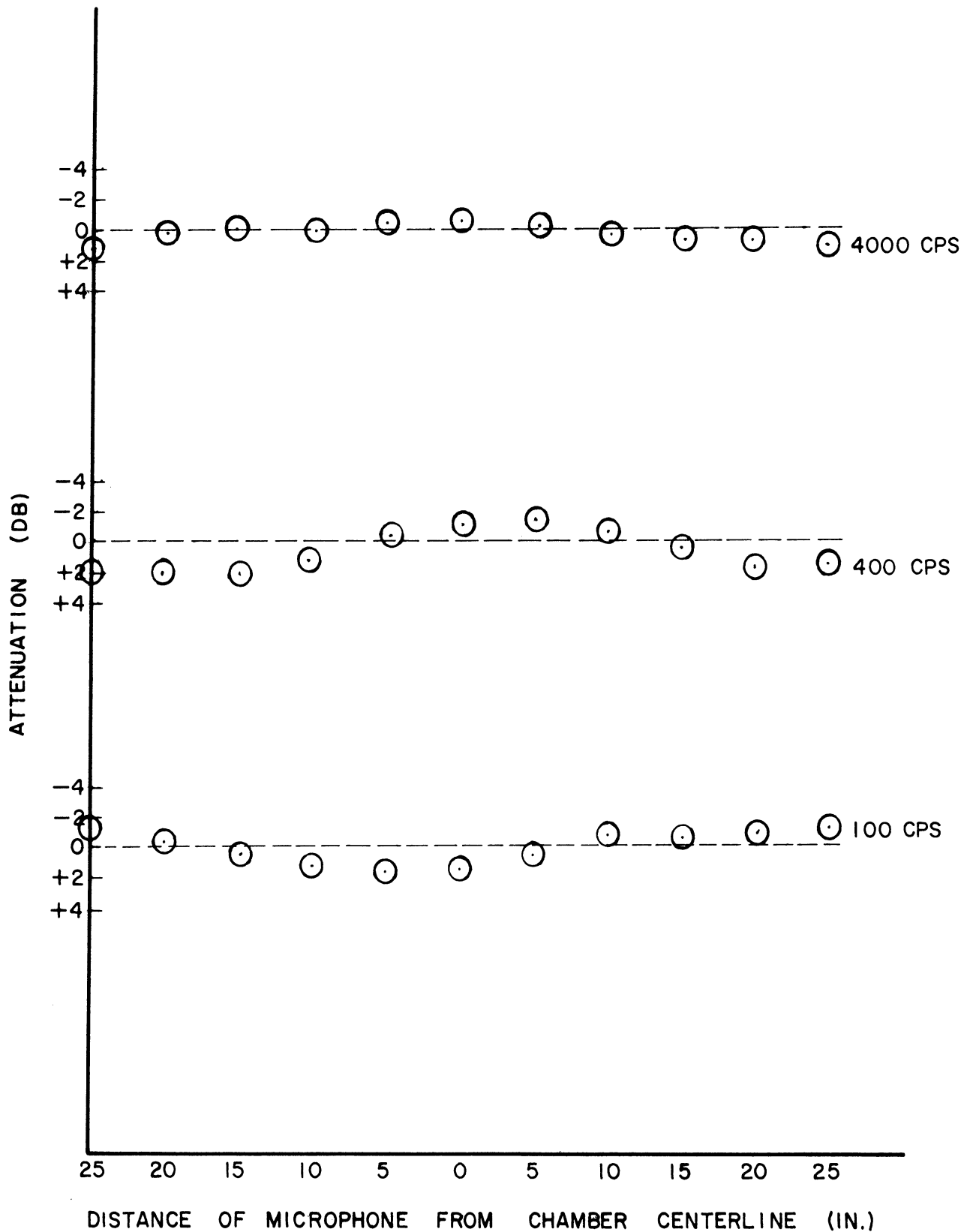


Fig. 13. Lateral surveys with terminal microphone.

wise arbitrarily located several feet apart. The pure-tone source was slowly swept through a frequency range and the ratio of the two microphone signals was recorded. Just as for the reverberation-room diffusion experiments, a smooth horizontal graph of sound-pressure ratio versus frequency should be expected in the absence of diffraction, coincidence, and standing-wave effects. This was found to be true except at frequencies below about 200 cps where lack of source diffusion was probably responsible for the observed excursions from a straight line.

3.4 TRANSMISSION EXPERIMENTS

The experiments described above were directed principally toward elucidating the behavior of individual components in the measuring system. In contrast to these, experiments were conducted to investigate the overall behavior of the transmission measuring system. Table II lists the apparatus employed in these transmission experiments.

TABLE II
APPARATUS FOR TRANSMISSION EXPERIMENTS

1. Warble-tone measurements, 17.5-in.-square window
a. Open window
b. 1/16-in. sheet rubber sample, 0.310 lb/ft ²
c. 1/8-in. sheet rubber sample, 0.668 lb/ft ²
d. 1/4-in. sheet rubber sample, 1.38 lb/ft ²
e. 0.020-in. bare aluminum panel
f. 1-in.-thick honeycomb panel (0.020-in. dural skin, 7/16-in. cotton cell) plus trim cloth
g. Series combination of 0.020-in. aluminum panel, 1-in. honeycomb panel and trim cloth [identical to structure No. 17 (Ref. 4)]
2. Pure-tone measurements, 17.5-in.-square window
a. Open window
b. 0.020-in. bare aluminum panel
c. 1-in.-thick honeycomb panel (0.020-in. dural skin, 7/16-in. cotton cell) plus trim cloth
d. Series combination of 0.020-in. aluminum panel, 1-in. honeycomb panel and trim cloth [identical to structure No. 17 (Ref. 4)]

It was decided to conduct these tests with a 17.5-in.-square transmission window for the following reasons:

1. All aircraft-type transmission samples on hand had been cut previously to fit the Small-Sample Aircraft-Transmission-Test Apparatus.
2. The testing of the same honeycomb sample configurations could provide experimental evidence corroborating the objections stated earlier regarding testing them on the Small-Sample Aircraft-Transmission-Test Apparatus.
3. It would simplify correlation experiments relating the two test methods for light, blanket-type samples for which the Small-Sample Aircraft-Transmission-Test Apparatus was devised.

The steel sample holder was removed from the Small-Sample Aircraft-Transmission-Test Apparatus and located in the 5-ft-square transmission window of the reverberation room by means of a 4-in.-thick wooden adapter frame as shown in Fig. 7. Thus, all previous sample configurations can be reconstructed for tests between the reverberation room and the anechoic termination.

3.4.1 Warble-Tone Transmission Experiments

The instrumentation used for these warble-tone transmission experiments is illustrated in Fig. 9. The source microphone (microphone No. 1, Fig. 9) was stationary and placed on center and 2 ft distant from the sample. The termination microphone (microphone No. 2, Fig. 9) was also stationary, on center, and 3-1/2 ft from the sample. The acoustic source was the loudspeaker mounted on the rotating reflector vane (location No. 4, Fig. 10). This was supplied with a nominal ± 20 -cps warble tone, modulated eight times per second in a linear-sawtooth manner and swept from low to high frequency at a rate of 1/8 octave per minute. The electrical signal power was maintained constant during each test (order of magnitude of one watt) and was sufficient to produce a sound-pressure level in the reverberation room of 100-db order of magnitude. The microphone calibrations (or interchange of microphone channels) were not taken into account explicitly during the present exploratory experiments, but this does not limit their validity and it can easily be accomplished in future work when more absolute measurements are desired.

Open Window Attenuation. The attenuation of the 17.5-in.-square opening as determined with the instrumentation described above is shown in Fig. 14. The apparent attenuation is significant magnitude at all frequencies and varies continuously across the spectrum. This attenuation curve is highly reproducible and certain characteristic features are readily apparent. An attenuation maximum occurs at about 180 cps, following which the attenuation decreases gradually to a broad minimum in the vicinity of 400 cps and then exhibits a generally increasing trend with increasing frequency. Other maxima are discern-

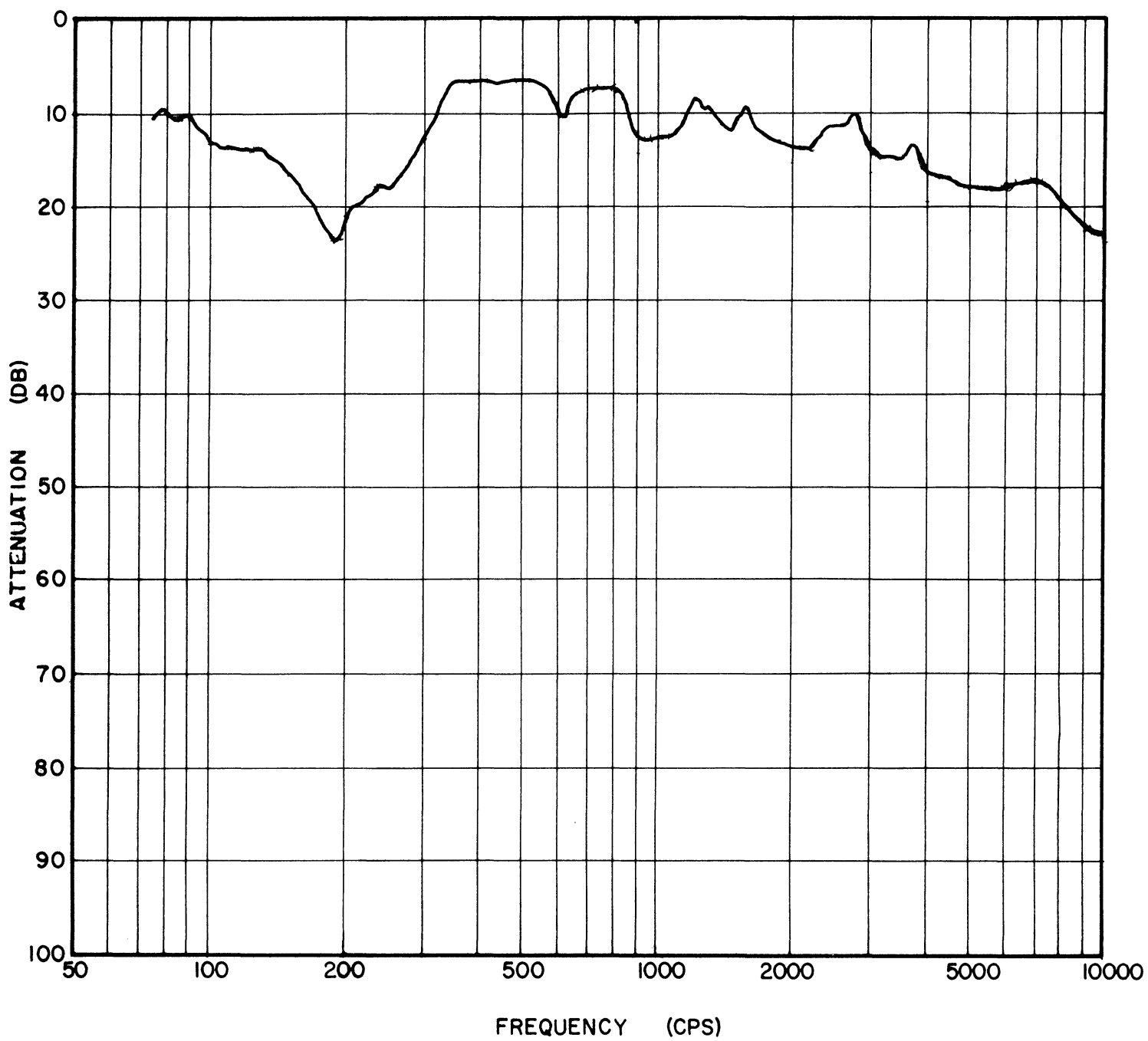


Fig. 14. Attenuation from 17.5-in.-square open window.

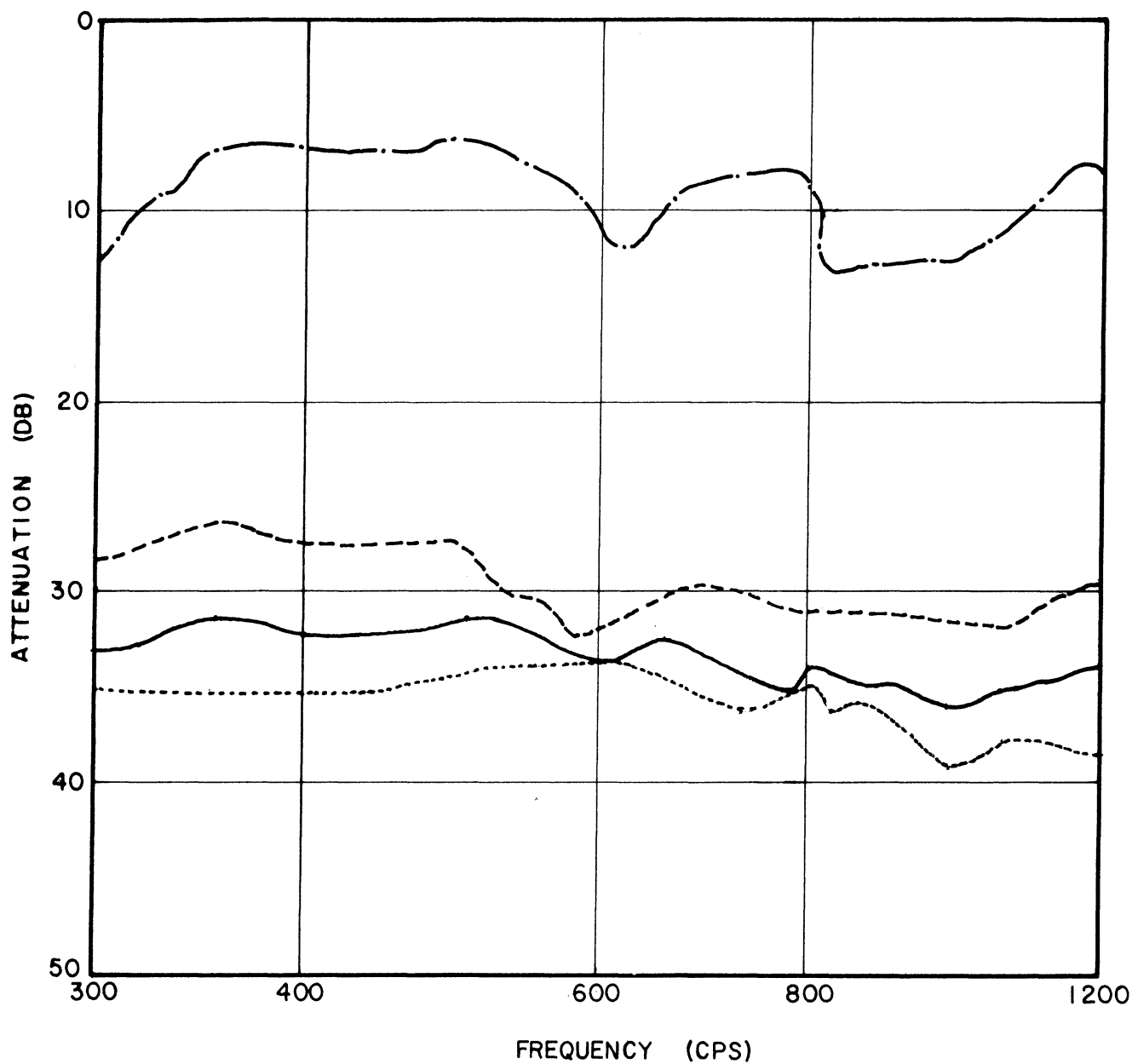
ible at 625, 825, and 1400 cps, and possibly at higher frequencies also. It is assumed that the attenuation properties of the open window are intimately linked to the opening configuration and to the volume and construction of the termination chamber, but not particularly dependent on the characteristics of the reverberation room. The validity of this assumption is indicated by later experiments in which the transmission of various samples was examined. In all cases, the detailed sound-pressure-level spectra from 75 to 10,000 cps obtained in the reverberation room (as recorded on one channel of the log. recorder, Fig. 9) were found to be identical, within experimental error, with that for the open window regardless of the nature of the sample.

Attenuation versus Surface Density of Sample. Since the apparent attenuation of a small open window exhibited considerable fluctuation as a function of frequency, it was decided to examine the apparent attenuation of other "known" samples over a limited frequency range. Three different thicknesses of soft sheet rubber were selected as suitable samples based upon the assumption of negligible panel stiffness and therefore "weight-law" transmission characteristics.

The results for this experiment are presented in Fig. 15 for a frequency range from 300 to 1200 cps. Several distinctive features are placed in evidence. The attenuation curves for the rubber samples exhibit less fluctuation as a function of frequency than does the curve representing the attenuation of an open window. This smoothing of apparent attenuation increases for the heavier samples. The attenuation curves for the three rubber samples are correctly ordered with respect to surface density and, over an appreciable portion of the frequency range, these curves are separated by approximately the expected amount. Also, the attenuation curve for the 1/16-in. rubber sample lies below that for the open window by an amount approximately equal to "weight-law" prediction (see Fig. 4). In the vicinity of 600 cps, however, all three attenuation curves crowd together, and near 800 cps, the curves for the two heavier samples nearly coalesce. The reasons for these convergences are not fully understood at present but they may be caused by vestiges of diffraction and standing-wave phenomena which were not uncovered in the earlier experiments.

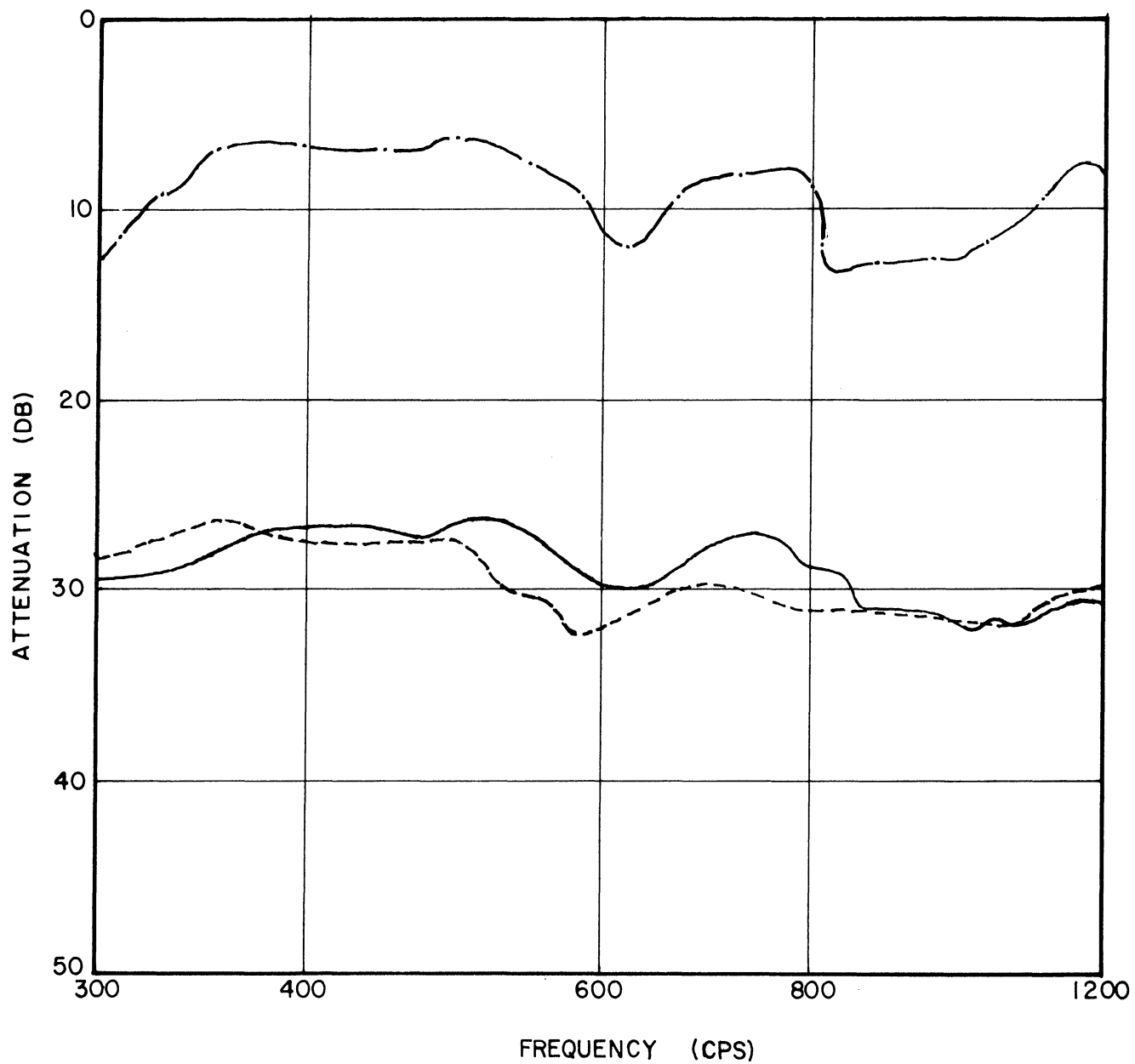
The 1/16-in.-thick rubber sample is only about 10% heavier than a 0.020-in.-thick aluminum panel (0.310 lb/ft² compared with 0.280 lb/ft²). This fact suggests a comparison of the corresponding apparent attenuations since the aluminum panel provides a degree of stiffness not present in the rubber sample. Figure 16 shows the apparent attenuations for the open window, the rubber sample, and the aluminum panel for the 300- to 1200-cps frequency range. On the average, the slightly heavier rubber sample exhibits larger attenuation, as would be anticipated, but the two attenuation curves differ considerably, in detail, presumably because of the greater stiffness of the aluminum panel.

A similar comparison between the 1/4-in.-thick rubber sample and the 1-in.-thick honeycomb sample (1.38 lb/ft² and 1.268 lb/ft², respectively) is presented in Fig. 17. A prominent transmission maximum occurs slightly above 500 cps for



— · — OPEN WINDOW, 17.5" SQUARE
 - - - 1/16" SHEET RUBBER, 0.310 lb/ft²
 — 1/8" SHEET RUBBER, 0.668 lb/ft²
 ····· 1/4" SHEET RUBBER, 1.38 lb/ft²

Fig. 15. Attenuation of sheet-rubber samples.

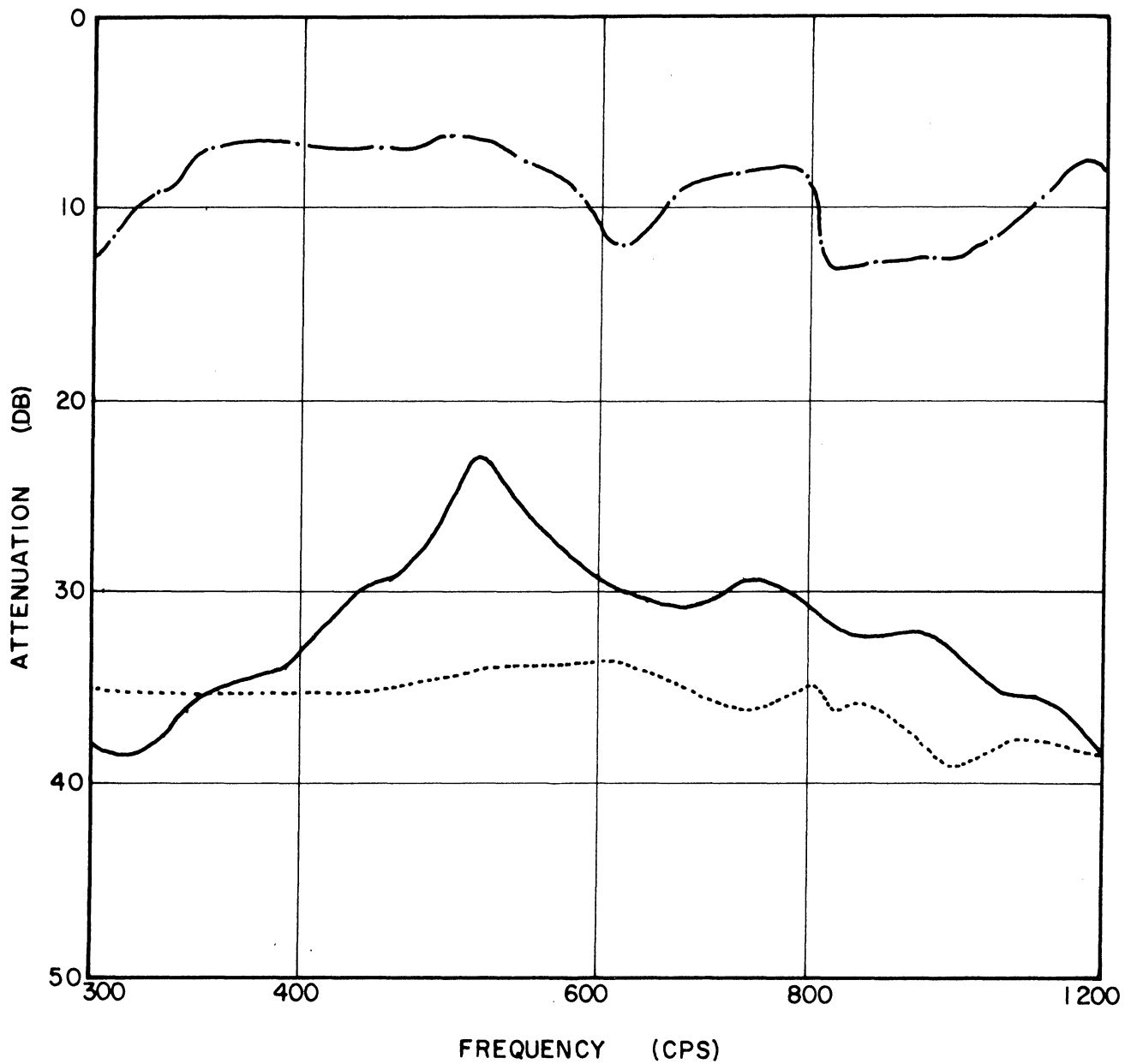


— · — OPEN WINDOW, 17.5" SQUARE.

- - - 1/16" SHEET RUBBER, 0.310 lb/ft²

— 0.020" ALUMINUM, 0.280 lb/ft²

Fig. 16. Comparative attenuation of aluminum and rubber samples.



— · — OPEN WINDOW, 17.5" SQUARE.
 1/4" SHEET RUBBER, 1.38 lb/ft²
 ——— 1" HONEYCOMB PANEL, 1.268 lb/ft²

Fig. 17. Comparative attenuation of honeycomb and rubber samples.

the honeycomb panel and the effects of its stiffness dominantly influence the apparent attenuation of the honeycomb panel up to at least 1200 cps.

Attenuation of Honeycomb Panel and Composite Sample. Rather than attempt extensive investigations to explain all the detailed behavior found during the above experiments, it was decided to undertake several warble-tone measurements covering the entire frequency range from 75 to 10,000 cps. To provide a comparison of test methods, a composite sample configuration was tested which was identical to one tested previously on the Small-Sample Aircraft-Transmission-Test Apparatus, namely, structure No. 17 (Ref. 4). This sample consists, in order from the source side, of the 0.020-in.-thick aluminum panel, a 2-in. air space, the 1-in.-thick honeycomb (0.020-in. aluminum skin, 7/16-in. cotton core), and finally, a trim cloth placed against the terminal side of the honeycomb. Additional transmission measurements were taken of the 17.5-in.-square open window, the 0.020-in. aluminum panel alone, and the 1-in.-thick honeycomb panel alone. The results from all four warble-tone transmission tests are presented in three graphs, Figs. 18a, 18b, and 18c, each representing a portion of the total frequency range. The apparent attenuation of the 17.5-in.-square open window was illustrated previously in Fig. 14 for the entire frequency range.

At low frequencies, that is, from 75 to 300 cps, the 0.020-in. aluminum panel yields less attenuation than either the honeycomb panel alone or the composite sample, but at higher frequencies this separation is not maintained. The prominent resonance found at about 525 cps for the honeycomb panel is conspicuously absent in the case of the composite sample. Probably the most obvious features of Figs. 18a, 18b, and 18c are the complexity of all curves, the difference in the characteristics of the detail observed for each curve, and the continual intersecting of the curves of the honeycomb panel and the composite sample. This last feature, of course, is an experimental manifestation of the objections raised previously to attempting transmission measurements of such samples on the Small-Sample Aircraft-Transmission-Test Apparatus.

It is fruitless to attempt further explanation of the detail found in Figs. 18a, 18b, and 18c at this time because, among other reasons, the sample size is too small for stiff panels and the clamping of the honeycomb panel is neither adequate, representative, nor particularly reproducible. It is important, however, to realize the potentialities of the testing method, particularly the potentiality to provide more information about a sample than any method utilizing octave-band or point-by-point large-percentage warble-tone measurements. The above experiments demonstrate clearly that the indiscriminate combination of individually effective partitions can be surprisingly ineffective.

3.4.2 Pure-Tone Attenuation Measurements

It had been observed during the reverberation room diffusion experiments that the use of a stationary pure-tone signal provided poor source-room diffusion at low frequencies (see Fig. 11). It was decided, therefore, to determine experimentally the extent of the confusion which might result if trans-

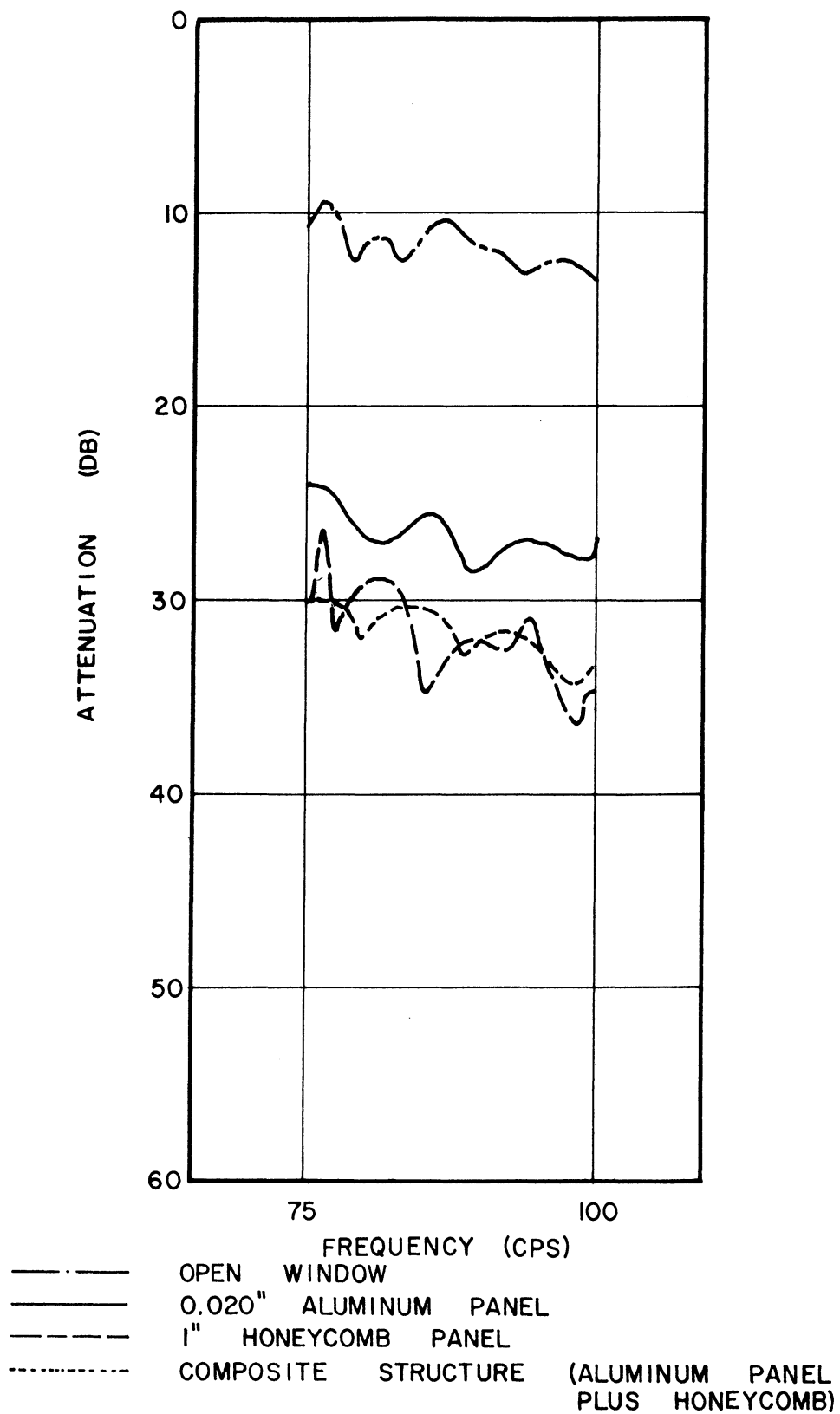


Fig. 18a. Warble-tone attenuation measurements.

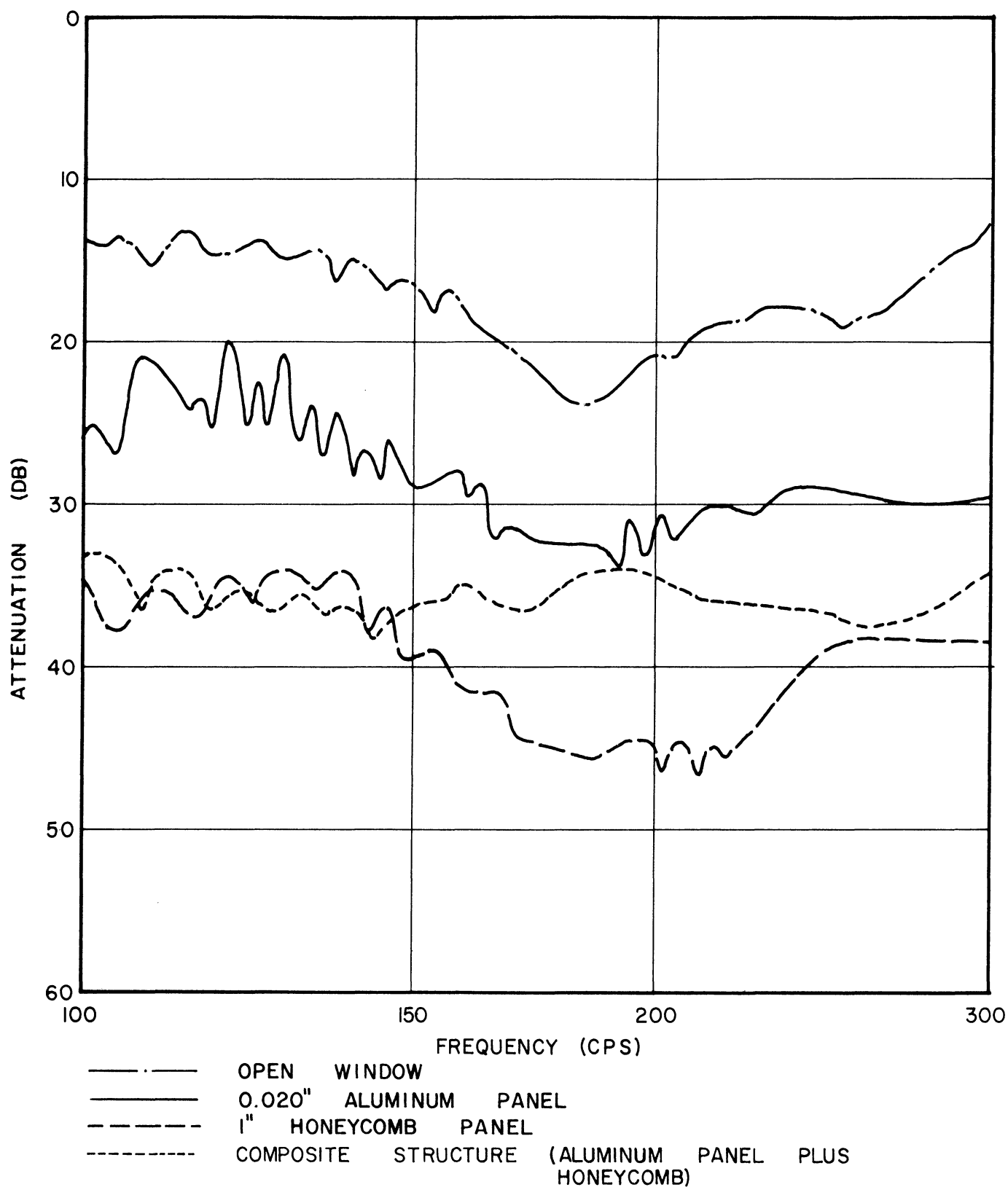


Fig. 18b. Warble-tone attenuation measurements.

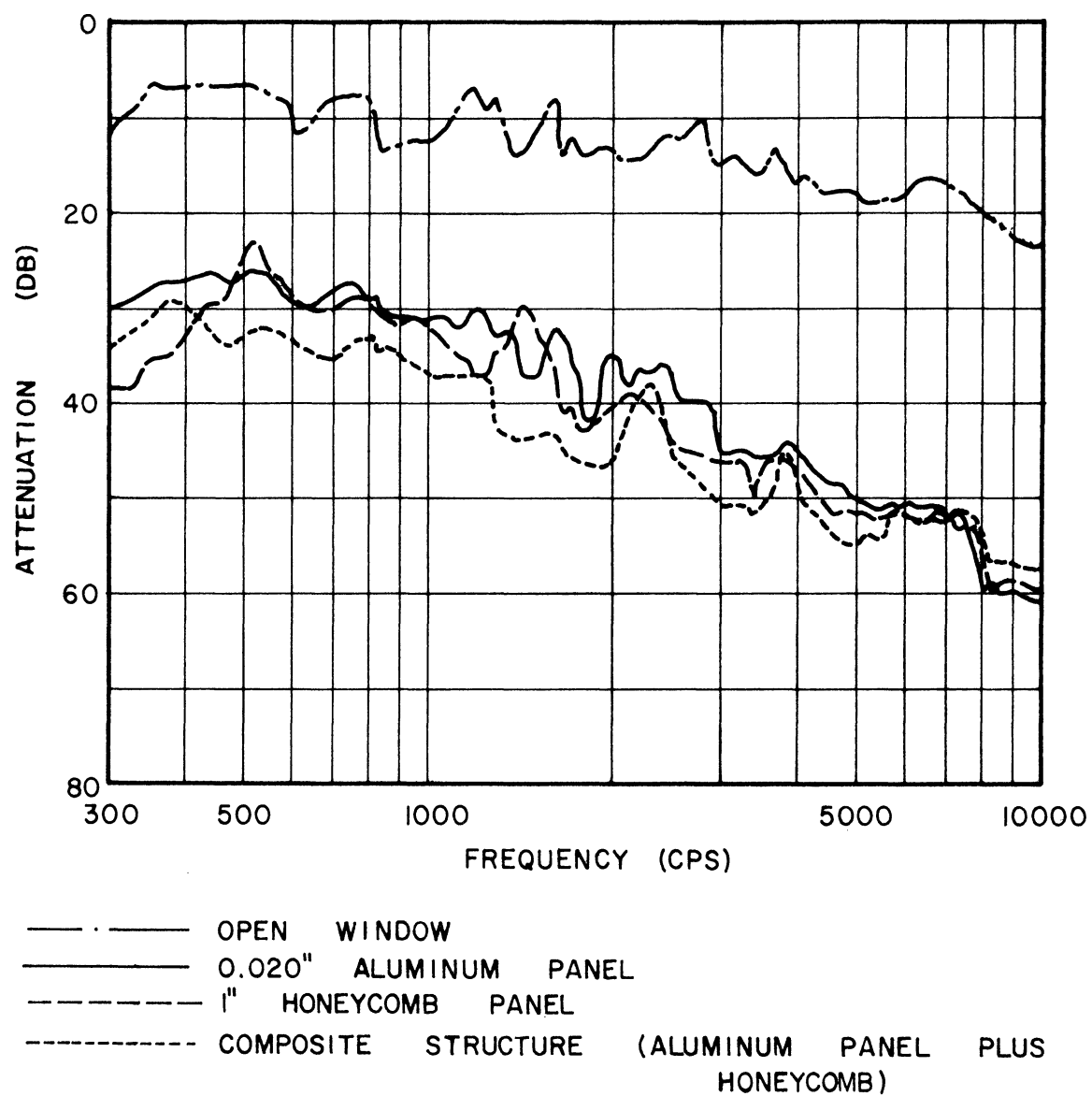


Fig. 18c. Warble-tone attenuation measurements.

mission measurements were undertaken with such source-room conditions. The experimental arrangements in the anechoic termination were identical to those used in the preceding warble-tone experiments. However, in reverberation room, a pure-tone signal was supplied to the stationary AR-1 loudspeaker and the microphone was mounted on the rotating reflector vane. The apparent attenuation was determined again under these new experimental conditions for the open window, the 0.020-in. aluminum panel, the 1-in. honeycomb panel alone, and the composite sample, with the results presented in Figs. 19a, 19b, and 19c.

An undecipherable complexity dominates the low frequencies up to about 180 cps, and some effect continues up to about 300 cps although the resemblance to the warble-tone experimental results becomes more evident. Above 300 cps, the natural diffusion of the reverberation room and the effect of the rotating vane are relatively sufficient and the use of a warble tone may not be necessary. Some differences between Figs. 18c and 19c can be observed, but no significance is attached to them because the samples and adapter structure had been disassembled several times in the interim. (Moreover, some variation in appearance is caused when the various figures are drawn, instead of being obtained by photographic reduction from an original chart recording as was Fig. 11.)

3.4.3 Subsidiary Experiments

The new warble oscillator (Bruel and Kjaer Type 1014) installed in the control console normally provides a linear-sawtooth modulation of constant but adjustable frequency excursion in contrast to the constant percentage sinusoidal modulation provided by the original instrumentation used with the Small-Sample Aircraft-Transmission-Test Apparatus. The sinusoidal warble oscillator has operated poorly in recent years, requiring much maintenance. Since the new Bruel and Kjaer oscillator was to be used for all future reverberation room experiments, some tests were conducted to determine if it could be used satisfactorily with the Small-Sample Aircraft-Transmission-Test Apparatus and if the transmissions so measured depended significantly upon the particular acoustic energy distributions caused by different warble characteristics.

Two tests were made with each oscillator: one for calibration purposes using only the standard 0.020-in. aluminum panel, the other with the complete structure No. 17 (Ref. 4) involving the aluminum panel, air space, honeycomb panel, and trim cloth. The original sinusoidal warble oscillator was operated with its normal $\pm 18\%$ warble at a rate of about eight times per second. The Bruel and Kjaer type 1014 oscillator also warbled at a rate of eight times per second but the following warble widths were selected to approximate the behavior of the original oscillator; that is, a nominal warble bandwidth of ± 20 cps was used from 58 to 120 cps, ± 40 cps from 120 to 180 cps, ± 60 cps from 180 to 370 cps, ± 80 cps from 370 to 523 cps, and ± 100 cps from 523 to 8800 cps.

The attenuation of the 1-in. honeycomb panel determined by using the two oscillators as described above is shown in Fig. 20, uncorrected for the assumed

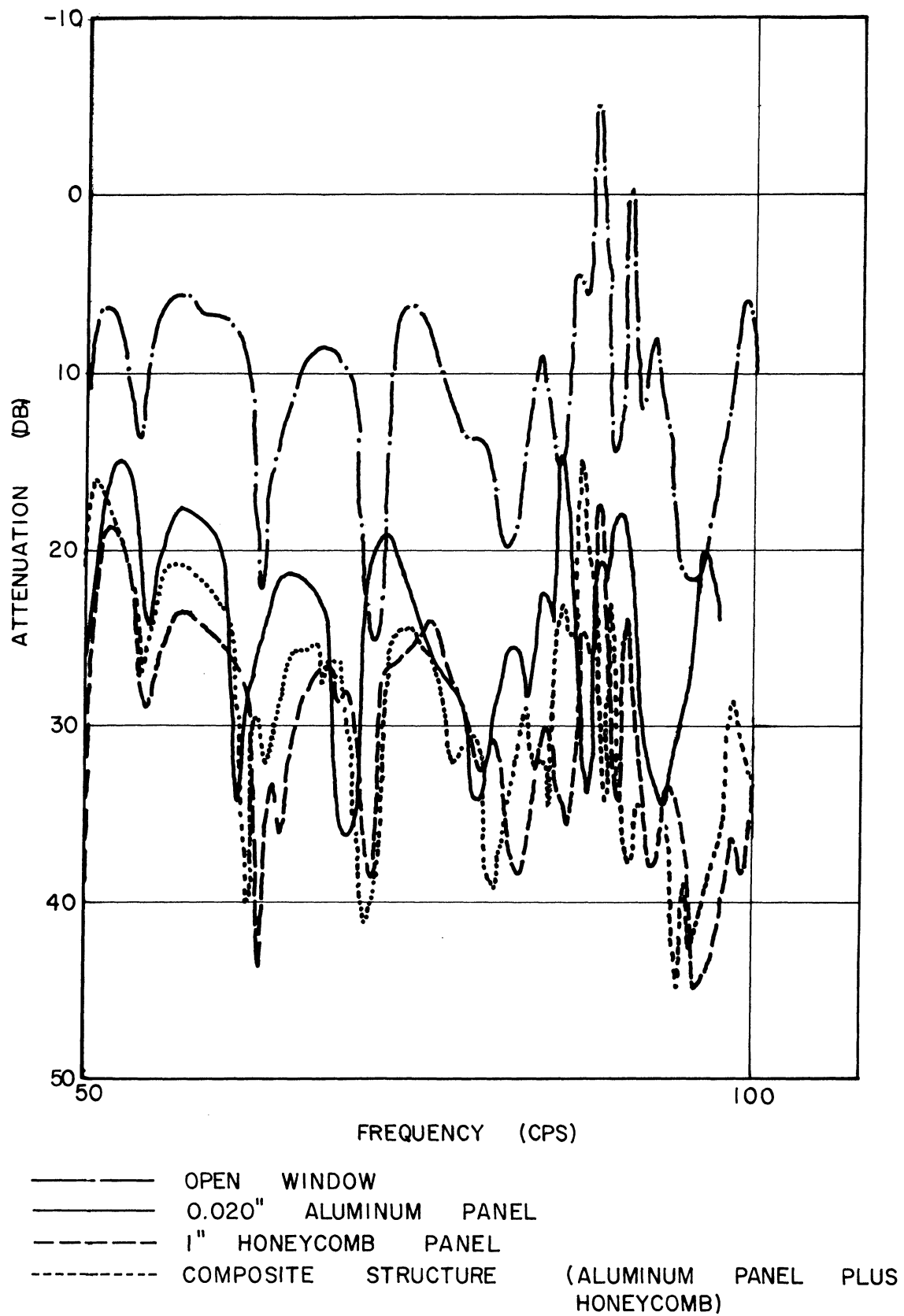


Fig. 19a. Pure-tone attenuation measurements.

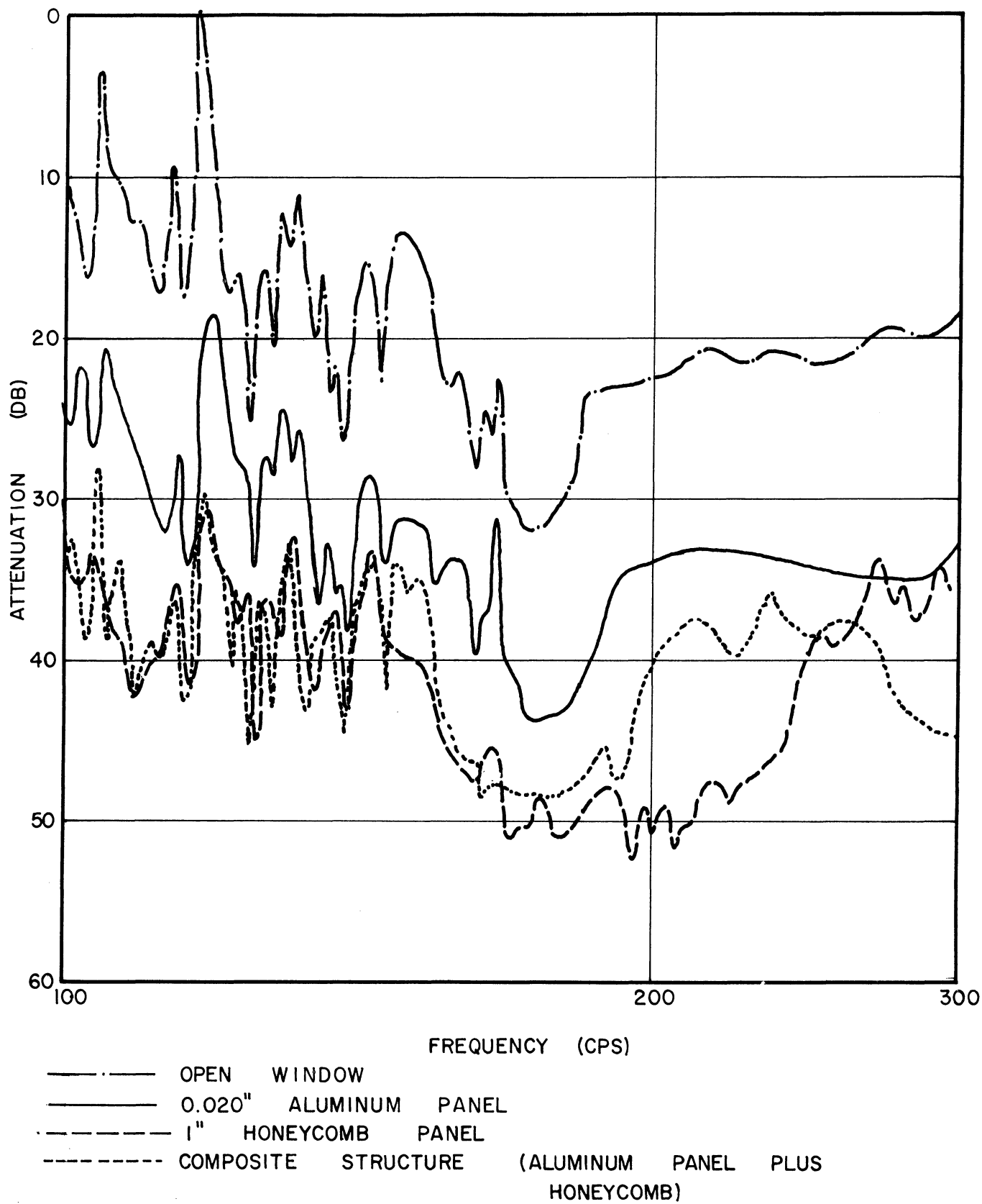


Fig. 19b. Pure-tone attenuation measurements.

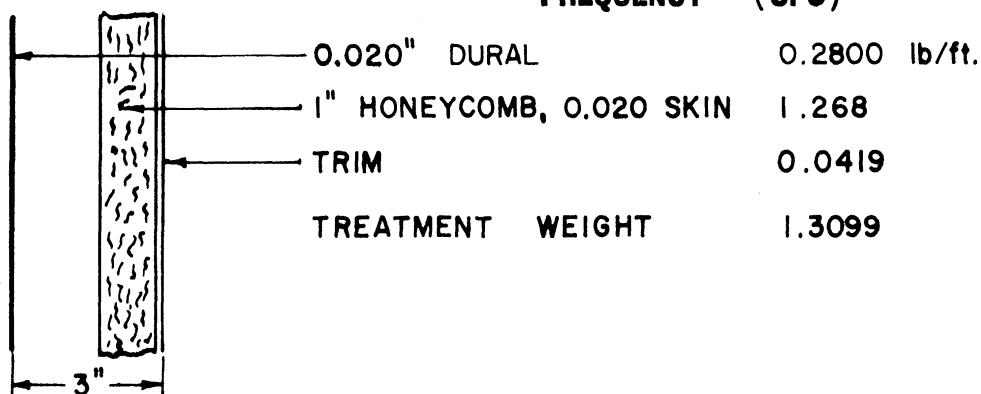
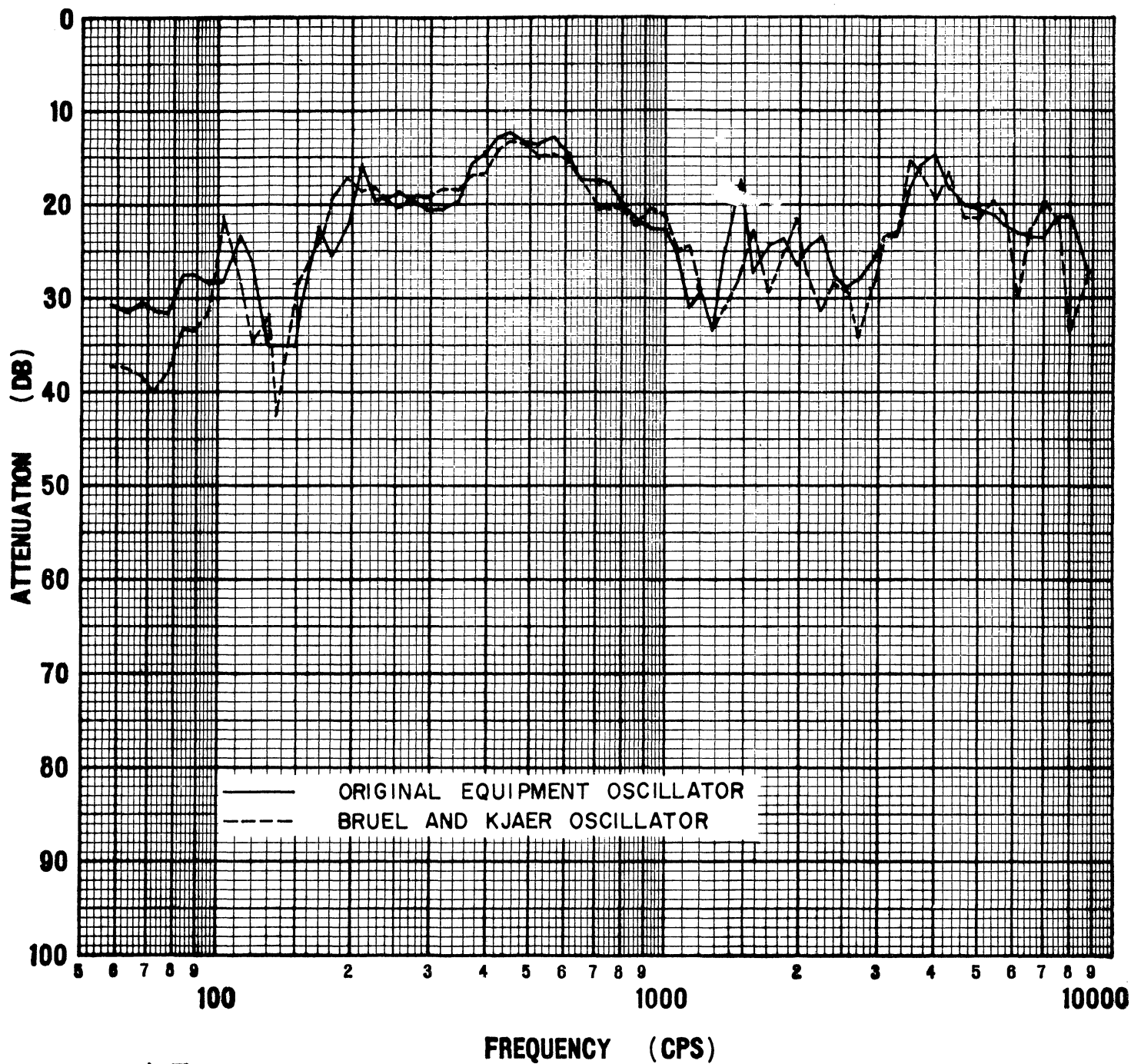


Fig. 19c. Pure-tone attenuation measurements.

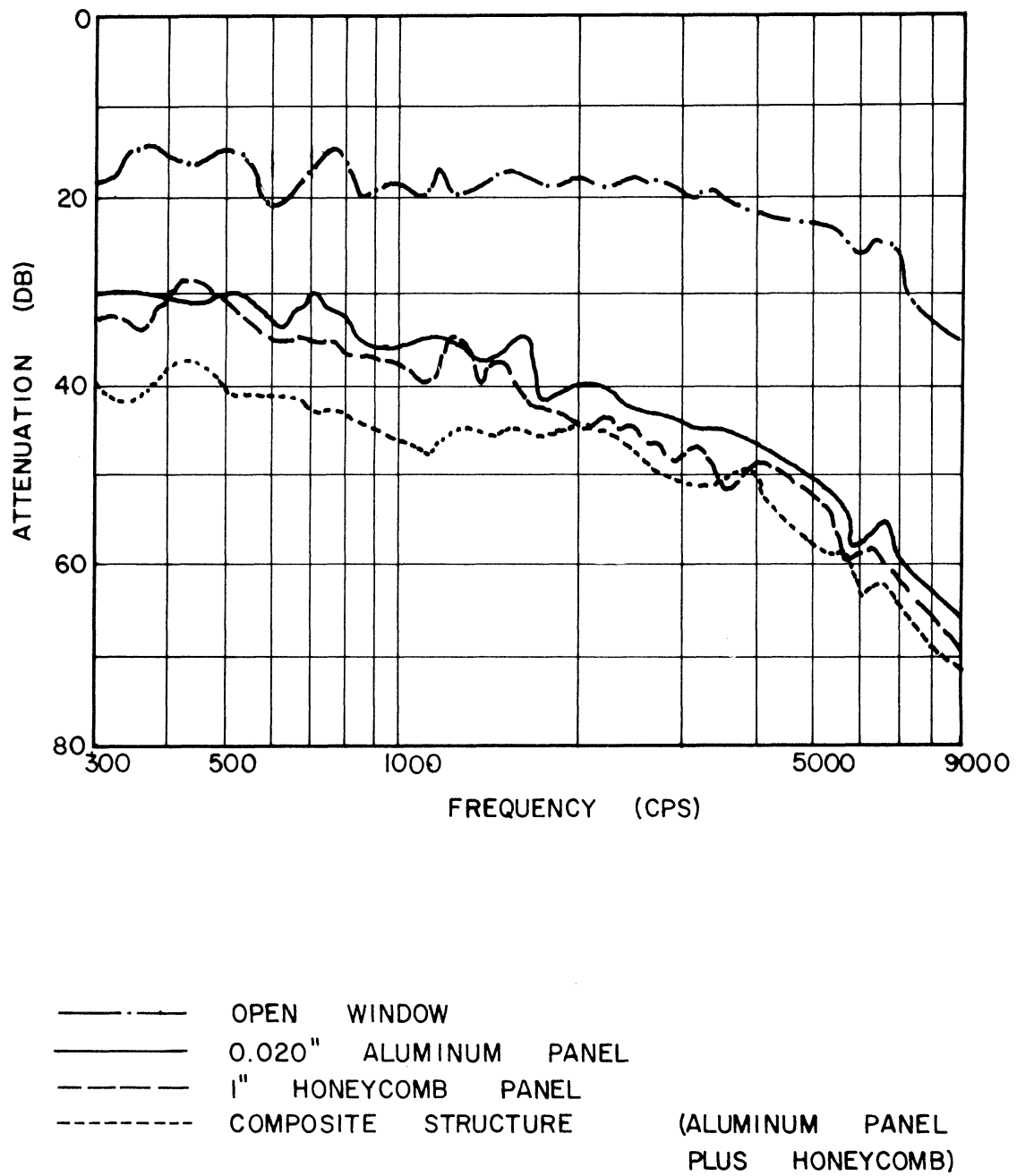


Fig. 20. Attenuation obtained with two different warble oscillators on small-sample aircraft-transmission-test apparatus.

weight-law behavior of the standard panel. In general, the agreement is good, although there are deviations at both low and high frequencies. At low frequencies, the deviations are probably caused by small dissimilarities in the energy distributions from the two types of warble, since both the warble rate and warble bandwidths were quite similar. At high frequencies, the warble bandwidth from the Bruel and Kjaer oscillator was definitely narrower than that from the original oscillator. This would result in less averaging and consequently more variation. Some of the variation, particularly at low frequency, may also be actual nonreproducibility resulting from the relatively unsuitable type of sample. Nevertheless, it appears that the new Bruel and Kjaer oscillator can be used successfully with the Small-Sample Aircraft-Transmission-Test Apparatus if reasonable precaution is exercised.

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