MODELLING APPLIED TO ENVIRONMENTAL ACOUSTICS

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NOTE

This is an abbreviated form of a contribution presented to the October 1975 meeting of the C.A.A. A few copies of a slightly more detailed version are available.

Introduction

In spite of the advent of modern digital computers, there are occasions when analogue methods are still the best approach to solving problems. Much interest in acoustic modelling exists around the world demonstrating that there is a commonly held opinion that the technique is prospectively a competitor to the numerical method and also that the numerical method has many shortcomings. It is possible to itemize the expected advantages of modelling. They are:

(a) Low cost, since cheap materials and simple measurements will be sufficient to provide satisfactory data;

(b) It should be more flexible than computing, i.e., able to deal with the most complex situations quickly and accurately;

(c) It will allow novel solutions to problems to be tried out and their effectiveness explored[1].

(d) In many cases it will be cheaper to use than numerical methods and will probably be able to deal with problems which would be beyond computational methods because of the complexities involved.

The first and most natural use of modelling is for the solution of barrier problems. This is a complex physical problem which is reviewed in detail in reference 2. It is a topic of interest to nearly all the major urban communities of the wealthier nations. It is not necessarily the most economic or effective solution to the control of traffic noise but undoubtedly it has its place and it is much used.

The nature of the physical problem is well understood. It is the application of diffraction theory which was first developed for the solution of optical problems. The basic problem can be stated to be that of solving Kirchhoff's equation, i.e.

$$\psi = \int_A a_1 \frac{fs}{dd_1} \left[\exp -ik(d+d_1)\right] dA \qquad (1)$$

(See Figure 1 for definition of symbols). Equation 1 can be directly applied to acoustics if air absorption is not important, simply by using the wavelengths and velocity of sound.

If we require a solution for many sources, then we look for the time averaged vector sum of their effects at P, i.e.,

$$\psi = \overline{\sum_m \int_A a \frac{fs}{d_m d_1} \exp \left[ik(d_m + d_1)\right] dA} \qquad (1a)$$

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If the sources are self coherent but incoherent with their fellows, if they are of varying strengths and of a complex frequency structure, these effects must be accounted for. In practice it is very difficult to solve the Kirchoff equation even for single point sources for anything but a relatively limited number of circumstances. S. W. Redfearn[3] solved the barrier problem using a solution to a similar equation from Carslaw's "Conduction of Heat".[4] His solution is not easily applied in practice and it neglects the presence of the ground.

Maekawa[5], in a series of papers, compared a theoretical treatment with the results of model experiments. His work is briefly summarized in Figure 2. Figure 3 shows a comparison of Maekawa's predictions with the field results obtained by J.M. Rapin[6]. A British Standard[7] gives charts based on treatment which solved the diffraction problem for a receiver and source both close to reflecting ground on which the barrier was built. Field assessments of this standard (and its later development) have been made and published by Scholes et al[8 9].

It is apparent that "semi-infinite" barriers make only a very rough approximation to the real state of affairs. In practice the barrier may be semi-continuous (e.g., with breaks for side roads, etc.). It might be built on undulating absorbing ground with multiple scattering effects of houses and other buildings and so on. These effects cause any theoretical treatment based on simple geometry to break down. The discovery that the prediction of one design procedure was inadequate was the major outcome of a study in Ontario by Harmelink[10]. In principle, we can deal numerically with any problem to any degree of accuracy (provided that sufficient time and trouble is taken). For many cases the complexity of the process involved almost defies description. Quasi-analytical solutions have their application to simple circumstances. Probably it is sensible economically to seek solutions by analogue methods for many if not most real circumstances.

Modelling Criteria

It is important to discuss what scaling laws must be satisfied in order to carry out satisfactory modelling. These are:

(a) Geometric similarity requires generally that λ/d for the prototype and the model must be the same. If λ/d is very large, as in the case of surface roughness for example, failure to preserve this ratio may not be significant.

(b) Time (t), for example, the passage of a vehicle between two points. If the linear scaling factor is given by:

$$S = \frac{d_M}{d_P} \qquad (2)$$

Using the suffix M for the model and P for the prototype, table Ia shows relationships for some quantities.

Table Ia

Quantity	Distance	Time	Velocity	Frequency
Scaling Factor	$d_M=d_P.s$	$t_M=s.t_P$	$V_M=V_P$	$f_M=f_P/S$

If time is scaled so that $t_M=t_P$ then the scheme shown in Ib occurs:

Table Ib

Quantity	Time	Velocity	Frequency
Scaling Factor	$t_M=t_P$	$V_M=SV_P$	$f_M=f_P$

Thus, if air is used for both prototype and the model then the velocity in each must be the same. Consequently the time for an event in the model is reduced. It follows that the model frequency must be increased*.

(c) Change of Medium. If for some reason another gas was used in the model then by writing

$$s' = \frac{C_P}{C_M} \quad (12) \qquad \text{it follows that} \qquad f_M = \frac{f_P}{ss'} \quad (13)$$

Two cases exist as s' can be greater or smaller than 1; the case that $s' > 1$ is, perhaps, more interesting. For example if we use a heavy gas such as krypton or freon 12, the model frequency can be reduced. Suppose $S = 1/80$, and air is replaced by freon 12 in the model:

$$S' = \frac{C_{air}}{C_{F12}} = 2.22 \quad .. \quad f_M = \frac{f_P}{2.22\ S} = 36\ f_P \text{ instead of } 80\ f_P.$$

Alternatively if f_M/f_P was maintained at 80, the model area available would be nearly five times more than would be obtained by using air. Similarly, if krypton is used $S' = 1.54$, $f_M = 52\ f_P$ and

if xenon is used, $S' = 1.92$; $f_M = 42\ f_P$.

(d) Surface effects in the model must represent their full scale equivalent. This means that the acoustic impedances in the model for the higher frequencies must be the same as in the prototype for the lower frequencies. Typically, two classes of materials are of interest in modelling urban environments:

(a) Hard materials of low absorption coefficient such as roads, pavements, and building facings.

(b) Porous materials of greater absorption coefficient such as the ground with its associated vegetation.

Delany, et al.[11] in their 1/30th scale model used the rough side of 3 mm hardboard to simulate the facing brickwork on buildings (the buildings themselves were constructed of 9 mm plywood). Roads and pavements (good sound reflectors) were simulated by using sheet aluminum. Absorbing ground with near-grazing propagation of sound[13] was simulated by 11 mm thick fibreboard. P.R. Donavan[12] in his 1/64th model of a city used plywood for the buildings which were constructed on a linoleum-covered concrete floor. Cann[1] tested the following materials and found them suitable: tree foliage, finely shredded paper; houses, painted styrofoam; roads, heavy flexible vinyl; ground, velour-covered fibreboard; and walls, heavy cardboard (covered with foam for absorption when needed).

(e) Air absorption presents a difficulty for modelling. Absorption is strongly dependent on frequency and humidity, Knudsen[14,15]. Delany et al.[11] and Donavan[12] all took account of this problem by correcting their model data for the extra absorption at high frequencies.

If we write $[\alpha d]_P$ and note that it scales to give $[\alpha d]_m$ then the ratio of these quantities gives the scaled classical absorption, these with related quantities are shown in table 1.

Acoustic Sources for Modelling

The spectrum of interest in traffic noise studies ranges from 50 to 2500 Hz, ref. Olsen[21], which for a model of 1/80th scale would convert to 4 to 200 KHz. A variety of noise sources have been been used for modelling. Cann[1], Delany et al.[11], Donavan[12], Lyon[22] have used broad band sources. Two of them used air jets, either impinging on each other or on vanes, while the others used spark discharges (which obviates the need for an anechoic chamber). Such devices suffer from the disadvantage that the frequency-amplitude relationship is fixed and uncontrolled. This inadequacy causes difficulties in obtaining a satisfactory correlation with the prototype, ref (11).

In order that the adequacy of the model may be fully investigated, and to have a better control over the noise source spectra, modulated whistles of the Hartmann type[23] are being developed for this project. With such devices intense sound of good tonal quality is easily obtained. Figure 4 shows a cross section of the prototype whistle. The essential features are (a) an over-expanded nozzle supplied with compressed air (typically about 600 kN/m^2 absolute), (b) an adjustable depth-cavity of 0.5 mm diameter bore, and (c) a means for adjusting the gap between the nozzle lip and cavity lip. Nozzle and cavity are the same bore and can easily be replaced with a different sized pair. The cavity needle allows the depth to be adjusted so that an octave-change of frequency can be obtained with nearly pure tone.

The performance of the whistle has been explored to find the effect of changes of;air pressure, gap size between the nozzle and cavity, and the cavity depth. Data has been obtained for whistles with 0.5 mm and 1 mm bore cavities. Figure 6 shows that nearly spherical emission is achieved by the whistle but some effect from the presence of the supports is apparent. The final design changes will be made to reduce their influence. Figures 7 and 8 show the variation of the frequency f and the whistle output L_T with cavity depth. The value of f calculated from $\lambda = 4(\ell + 0.3d)$[24] is in good agreement with experimental data. Figure 9, for a fixed geometry indicates that f varies little with pressure whereas L_T is strongly affected (with a maximum at 60 lb f/in^2).

These results show that it will be possible to span the required frequency range using fixed geometry, variable cavity depth, whistles producing a very adequate power level. It is intended to modulate the cavity needles by means of an electrically driven piezo-electric bimorph element. In this way it should easily be possible to produce any time averaged sound spectrum which is required.

The Calgary Model Facility

Since continuous ultrasonic noise sources will be used in this facility, it is necessary to find suitable materials for a high frequency anechoic enclosure of the model. To this end a 1 m^3 steel reverberation chamber was built (see Figure 10). The prototype whistle was used as a source. Proposed materials for the anechoic chamber were placed in the reverberation apparatus and their absorption coefficients found. Figure 11 shows the completed chamber. It should be noted that most of the wall panels can be removed in order to have free access and consequently the whole of the chamber floor space can be filled by the model.

Conclusions

This paper outlines a literature review which has been conducted; the review indicates that modelling probably will be a useful and successful technique. The application of scaling laws to the problem have been reviewed and commented on. The need for a thorough and careful approach to the problem in which all the material properties are measured and in which a controlled sound source is employed appears to be indicated. The development of a well-controlled high frequency source is described, together with some description of the first measurements of material properties. Experience to date indicates that modelling should provide a low cost method for obtaining solutions to propagation problems.

Acknowledgement

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Table 1

CLASSICAL ATTENUATION AT ≈15°C, 1 ATMOSPHERE

	CONDUCTION $\alpha_c/f^2 x10^{11}$ s^2/m	VISCOUS $\alpha_v/f^2 x10^{11}$ s^2/m	TOTAL $\alpha/f^2 x10^{11}$ s^2/m	C sound speed m/s	$(\alpha d)_M/(\alpha d)_P$
AIR (DRY)	0.38	0.99	1.37	332	80
NITROGEN	0.39	0.96	1.35	334	80
HELIUM	0.22	0.31	0.53	965	90
KRYPTON	1.25	1.80	3.05	219	117
XENON	1.43	2.06	3.49	175	107
FREON-12	0.24	1.95	2.19	150	58

Effects relating to molecular relaxation processes may modify some of the values given in the table. Some data relating to this effect is not available and none is listed. It is to be noted that the effects of molecular absorption can be reduced either by drying the air used in the model or replacing it with a nitrogen atmosphere. Figure 12 shows the values of α/f^2 for wet and dry air and nitrogen. More information on this topic can be found in references 14 to 20.

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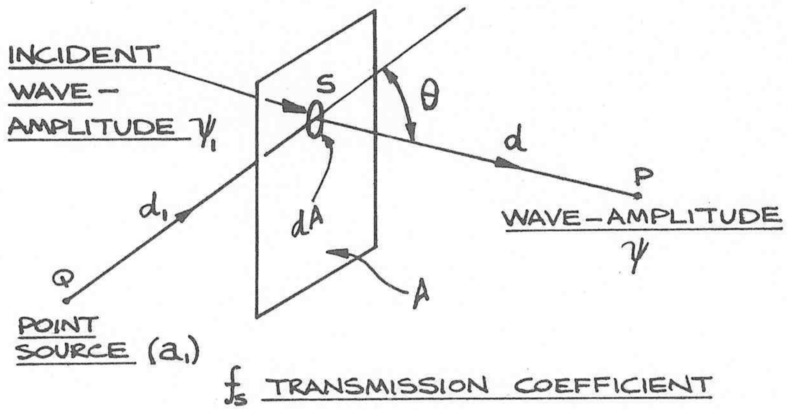
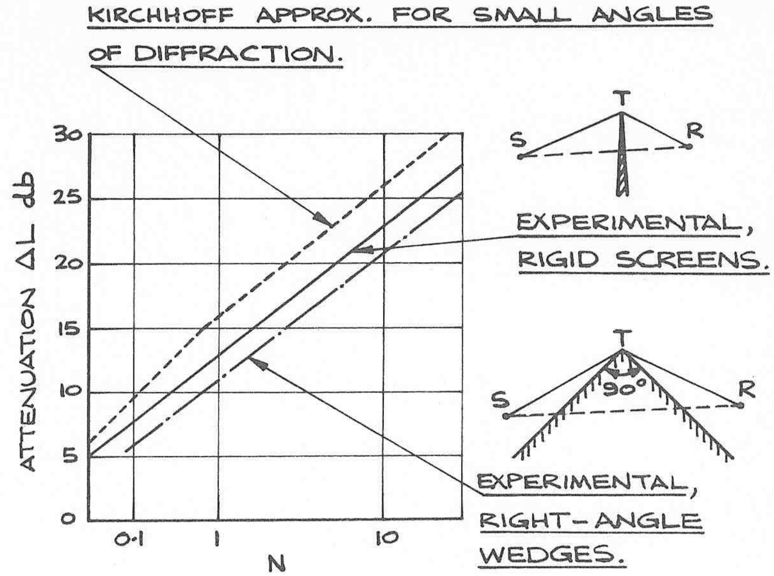
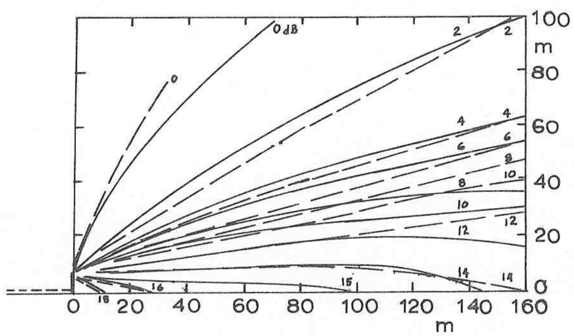


FIGURE 1



$N = \frac{2\delta}{\lambda}$ $\quad\delta$ = PATH DIFFERENCE = STR – SR

FIGURE 2



Section normal to eight-lane highway. —— Data from model test by Rapin[6] . ---- Calculation wtih Mackawa's procedure.

FIGURE 3

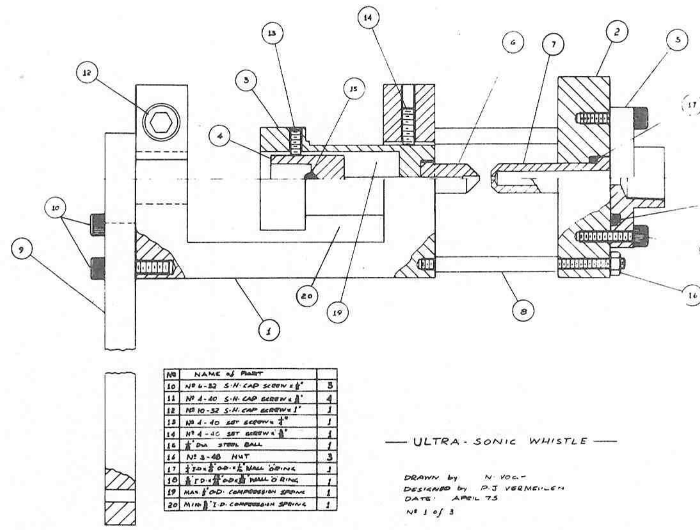
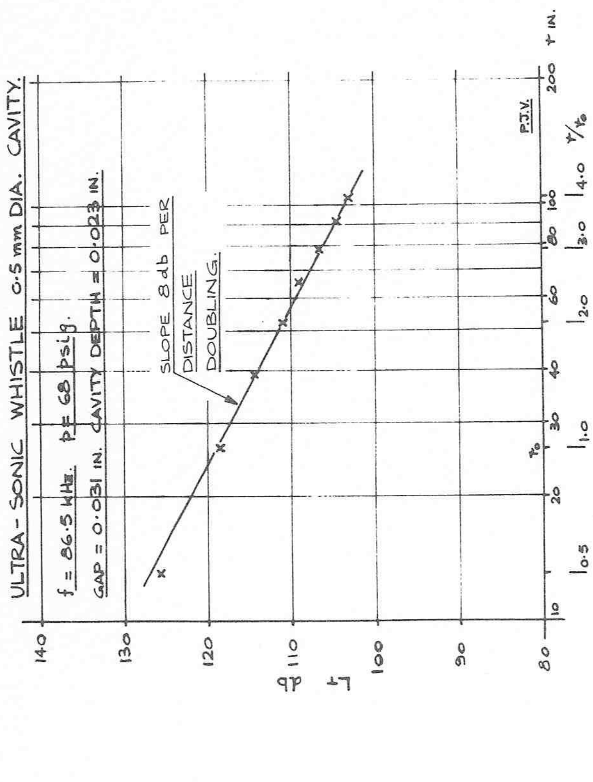


FIGURE 4



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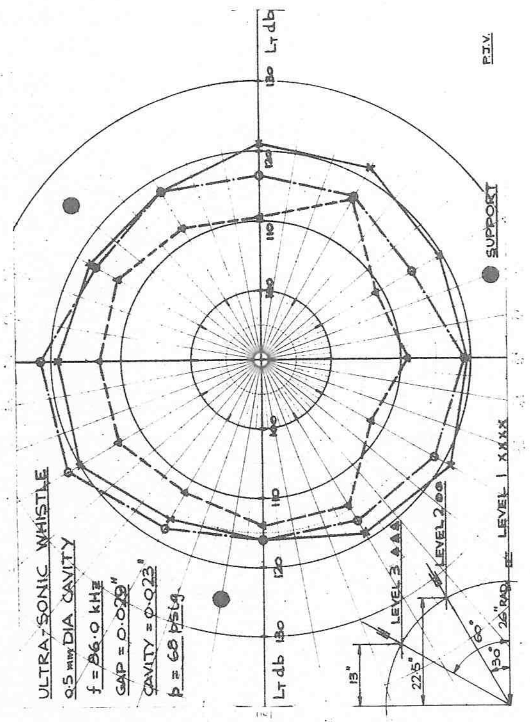

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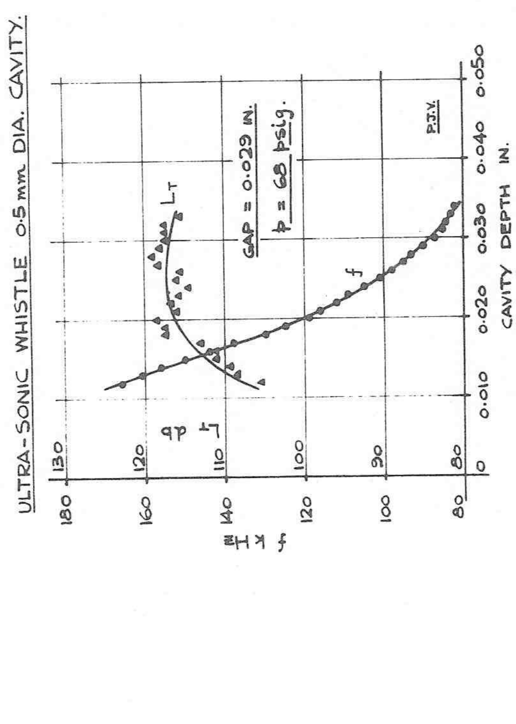

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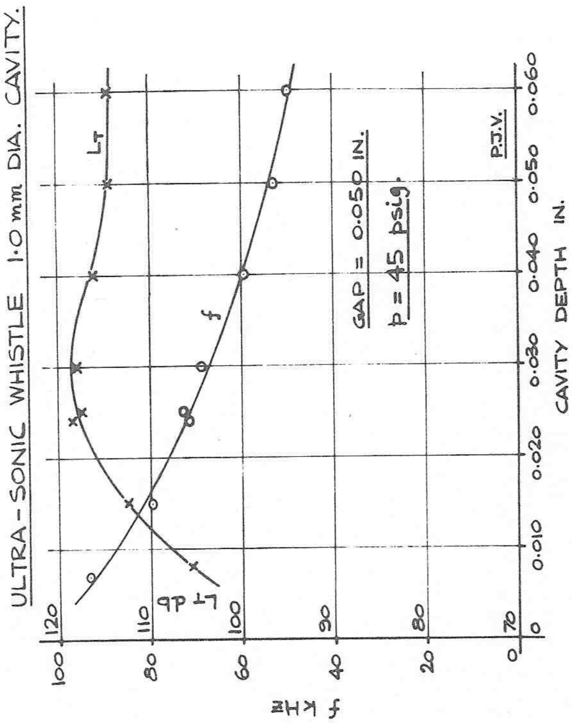

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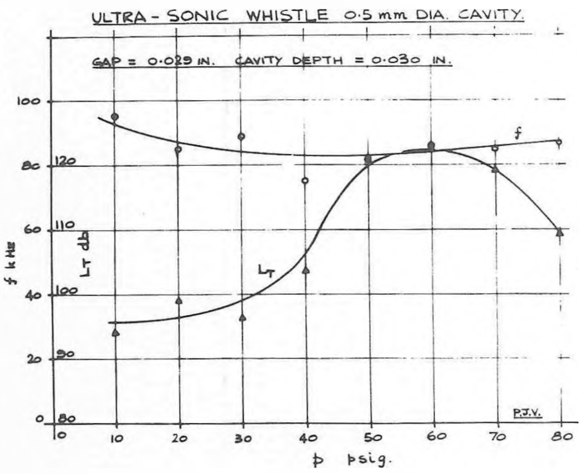

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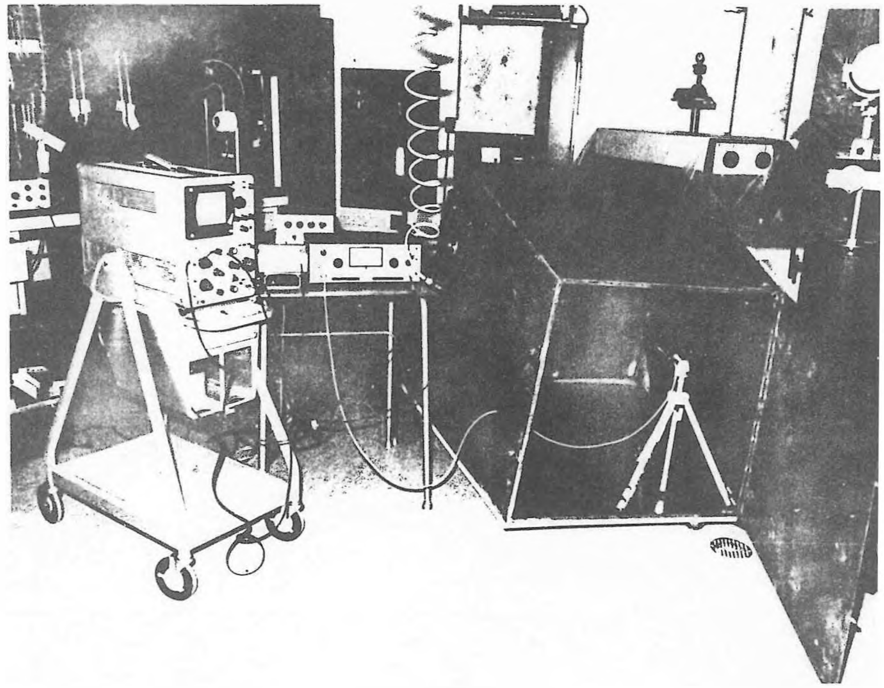

FIGURE 10

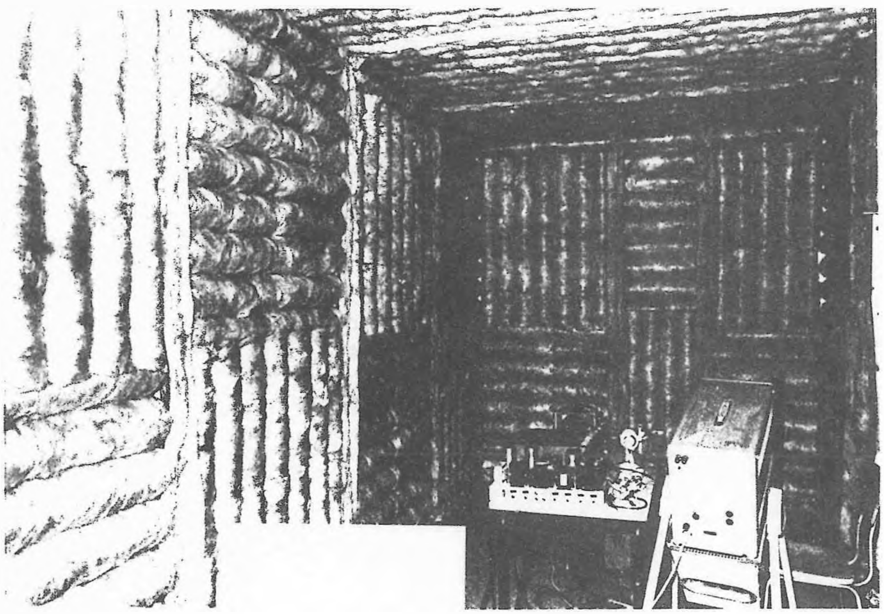

FIGURE 11

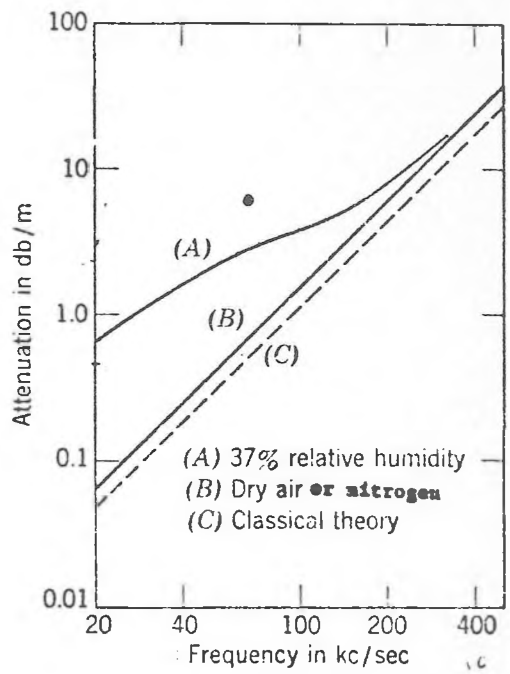

FIGURE 12