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TRANSMISSION - LOSS MEASUREMENTS USING A CORRELATION TECHNIQUE

BY

R. J. DONATO

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**LA MESURE DE LA PERTE PAR TRANSMISSION AU MOYEN D'UNE
METHODE DE CORRELATION**

SOMMAIRE

L'auteur considère les avantages et les désavantages d'une méthode de discrimination de temps pour mesurer la perte par transmission à travers un mur. Contrairement aux méthodes existantes, on emploie en tout temps un appareil analogique à large bande et l'on améliore la discrimination au moyen d'un filtre dit "pre-whitening" avant la corrélation.

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Transmission-loss measurements using a correlation technique

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The merits and demerits of using a time-discrimination technique to measure transmission loss through a wall are discussed. The method differs from those previously reported in that a wideband analogue approach is used throughout and the discrimination is improved by the use of a pre-whitening filter before correlating.

Subject Classification: 2.9.

INTRODUCTION

The normal method of evaluating the transmission loss of a wall is to place the wall between two reverberant rooms. One room is used as the exciting enclosure and helps to ensure that a diffuse sound field strikes the wall. The other room is used as a receiving integrator and sums the energy transmitted through the wall.

Sometimes, especially in field measurements, the measurement cannot be made between isolated enclosures and the problem of flanking occurs. Even in the laboratory it would occasionally be useful to have an approximate estimate of the properties of a wall without the trouble of using the reverberant facility.

The problem is fundamentally one of time discrimination. One method would be to use a pulse technique by amplitude modulating a carrier frequency. The main difficulty with such a technique is to obtain a reasonable-looking pulse, especially after its transmission through a highly attenuating mechanism like a wall. Most loudspeakers, for instance, tend to ring and the low-frequency ringing tends to mask the higher-frequency components in a pulse, especially at higher carrier frequencies. The pulse quality deteriorates and makes measurements difficult. The correlation approach employs the same principle of time discrimination, but pulses and their attendant problems are no longer needed and the analysis can be made using a band of frequencies. Such a technique has been used by Burd¹ and more recently by Schomer.² It was, in fact, this latter paper that prompted the author to report these measurements made some years ago. Interest in them at the time waned because the measurements were for discrete angles of incidence; to evaluate the transmission loss as normally understood,³ one would have to integrate the discrete-angle results over a hemisphere. It is in this area that the practical worth of the technique becomes questionable.

Where the method described in this paper differs from Schomer's is not in the principle but in the technique. Whereas Schomer uses a digital technique throughout, with the Fourier transform of the cross-correlation function performed by computer, we use an analog

correlator followed by an analog heterodyne analyzer. The important item is the correlator that retains analog voltage information of the correlation function for a set of time delays, and these voltages are then played sequentially and periodically through various analog processing devices.

I. THEORY

The theory has been adequately described² and need only be outlined here. We take the time output waveform of the sound source to be $s(t)$ with a Fourier transform of $S(\omega)$, the impulse response functions of two microphones spaced either side of the wall to be $m_1(t)$, $m_2(t)$ with transforms $M_1(\omega)$, $M_2(\omega)$, and the impulse function of the wall $h(t)$ with transform $H(\omega)$. If m_1 is the microphone on the source side, then the correlation between microphone signals will be the correlation of $s(t)*m_1(t)$ with $s(t)*m_2(t)$, where $*$ represents convolution.

As correlation is backward convolution, we may write for the correlation between the microphones with no wall in place

$$r_1(\tau) = s(\tau)*m_1(\tau)*s(-\tau)*m_2(-\tau), \quad (1)$$

and the Fourier transform $R_1(\omega)$ will be

$$R_1(\omega) = [S(\omega)]^2 M_1(\omega) M_2^*(\omega). \quad (2)$$

With the wall in place we must substitute for the output of microphone m_2 the expression $s(\tau)*h(\tau)*m_2(\tau)$. Thus

$$r_2(\tau) = s(\tau)*m_1(\tau)*s(-\tau)*h(-\tau)*m_2(-\tau) \quad (3)$$

and

$$R_2(\omega) = [S(\omega)]^2 M_1(\omega) M_2^*(\omega) H^*(\omega). \quad (4)$$

Thus, from Eqs. 4 and 2,

$$R_2(\omega)/R_1(\omega) = H^*(\omega). \quad (5)$$

In the reverberation room technique we consider energies and effectively measure $[H(\omega)]^2$. Thus the quantity we need to measure is the modulus of the transfer function (superscript $*$ is the complex conjugate).

FIG. 1. Block diagram of analyzer.

II. EQUIPMENT AND EXPERIMENTAL CONSIDERATIONS

Figure 1 shows a block diagram of the equipment. The correlator allowed 100 points to be displayed over a variable total delay range. To prevent aliasing with signals in a band 50–5000 Hz the total delay range was 10 msec. Thus a 5-kHz signal may be just about resolved. The microphone on the source side was almost 4 ft from the wall and the one on the receiving side only 6 in. The loudspeaker source was 8 ft from the wall. The wall itself was about 8 ft high with the frame adding another 6 in. all around. The frame itself stood about 1 ft off the floor. The microphones were about 5 ft below the top of the frame. Thus the flanking path from the wall top just exceeded the 10-msec correlator delay. The flanking path from below the wall was obstructed by boarding.

The effect of the wall is to reduce the high frequencies and this of course broadens the cross-correlation pulse. To keep the correlation function crisp, a high-pass filter was included in one of the inputs to the correlator. This prevents the correlation function from spilling into the flanking path signal. The correlator read-out has a maximum rate of two points each millisecond. Thus the frequency content of the output is scaled down by a factor of 5. The correlator output display was externally triggered to repeat at 80-msec intervals. Thus the output frequency spectrum was effectively passed through a comb filter at 12.5 Hz spacing. Ideally, we should like to analyze the output waveform using $\frac{1}{3}$ -octave filters. In view of the frequency scaling and frequency spacing, however, we would have few components at each low-frequency setting. The results, then, are critically dependent on the relative phases of these components and could lead to erroneous conclusions. The problem could be solved partially by

reducing the pulse repetition frequency, but the energy would be reduced and the same problem would merely appear at higher frequencies. The solution adopted was to pass the correlation function through a heterodyne analyzer with a bandwidth less than 12.5 Hz, viz 10 Hz. The effect of $\frac{1}{3}$ -octave filtering was introduced by averaging the analyzer output with a fairly long time constant. For a sweep of 1 kHz, occupying 50 sec, the time constant was made 1 sec.

III. RESULTS

Figures 2, 3, and 4 show the transmission loss as calculated from Eq. 5. On each graph the reverberation room results are shown for comparison. The correct trends are present in that as the angle of incidence increases the transmission loss decreases. Only three incident angles were used, 0°, 30°, and 60°. The wall was lightweight concrete and should display a critical frequency of about 400 Hz. The reverberation room results show some plateau effect in the 400-Hz region but the normal incidence results, of course, do not show any coincidence effect. The slope is around the theoretical 20 dB/frequency decade. With angles other than normal the slope seems to be split into two parts.

Plane wave theory forecasts that for frequencies below coincidence the slope should be 20 dB/decade and above coincidence 60 dB/decade. This may be seen from the classical formula for sound transmission loss τ :

$$(\tau)^{-1} = \left[1 + \left(\frac{\eta \omega M}{2 \rho c} \right) \left(\frac{f}{f_c} \right)^2 \cos^2 \Phi \sin^4 \Phi \right]^2 + \left(\frac{\omega M}{2 \rho c} \right)^2 \cos^2 \Phi \left[1 - \left(\frac{f}{f_c} \right)^2 \sin^4 \Phi \right]^2,$$

FIG. 2. Transmission loss at normal incidence.

where M is the surface mass, ρc the characteristic impedance of the surrounding medium, f_c the critical frequency, and η the damping factor. The slope change is evident on Figs. 3 and 4, but the steeper slope is 30 dB/decade rather than 60 dB/decade. It would appear that the reason for this discrepancy lies in the nature of the source waves, which are far from unidirectional. For a diffuse incident sound field we would find, for frequencies greater than critical, an f^2 dependence. One would expect a similar dependence for a point source. This can be seen by the Sommerfeld conversion of a spherical wave to a series of cylindrical waves. We thus have to consider expressions of the type

$$\int_0^\infty J_0(kr)F(k)kdk e^{-\nu z}/\nu,$$

where r is the direction along the wall, k the wavenumber in the wall, z the direction perpendicular to the wall and $\nu = (k^2 - k_a^2)^{1/2}$. The quantity $F(k)$ is the effective admittance of the wall and has a peak at the coincidence point.

Thus a whole series of coincidence points, one for each frequency above the critical, will be presented. Of course, the source is not really a point source and will have its own directivity pattern, possibly of the type $J_0(af \sin\Phi)/af \sin\Phi$ where a is a constant and Φ is the angle from the axis. For each coincidence frequency the angle will change so that both Φ and f will vary in the directivity term. For the higher frequencies the angle will approach normal to the wall and the transmission will vary as f^{-1} from this cause. With the f^2 dependence this will make an f^3 dependence for the transmission law. For angles near the axis of the source both f and $\sin\Phi$ vary; this will cause the relatively slowly changing

FIG. 3. Transmission loss at 30° incidence.

FIG. 4. Transmission loss at 60° incidence.

directivity with either parameter to become steeper. In all, the f^3 relation seems reasonable.

Although the change of slope in the transmission curve of Figs. 3 and 4 is pronounced, the frequencies at which the breaks occur do not seem to conform to their theoretical predictions. Considering dispersion of flexural waves in the plate, one would expect the coincidence frequencies for plane waves at an angle of 30° to be three times the value at 60°. It must be mentioned that the curves have been smoothed before plotting. Inspection of the original data reveals peaks at 400 and 1300 Hz for the two angles. These are consistent over several records and although the records are far from smooth one could interpret these peaks to be coincidence effects. On the whole and in view of the point source argument, one would tend to treat any conclusions drawn from the location of these peaks with caution.

IV. CONCLUSIONS

The real test is what to do with the data obtained by this method. To compare this method with the standard method one would need to integrate over a range of angles. The main advantages would be in field measurements, when flanking effects would normally influence the results, or in quick laboratory checks where one angle of incidence would be sufficient. To the extent that the basic technique has application, the present arrangement has some advantage over previous versions in the use of the prewhitening filter, which helps preserve the time discrimination, and in the large amount of data that may be stored using an analog device.

A more pertinent criticism is that the discrete angles are not really discrete; because of the point source, one

obtains results from a range of angles. Thus one has neither the plane wave nor the diffuse field condition. It would seem to be best to concentrate on the normal incidence case and obtain results that should be greater than for the diffuse field case. We find, in fact, that the results are greater only at the lower frequencies.

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¹A. N. Burd, "Correlation Techniques in Studio Testing," *Radio Electron. Eng.*, 387-395 (May 1964).

²P. D. Schomer, "Measurement of Sound Transmission Loss by Combining Correlation and Fourier Techniques," *J. Acoust. Soc. Am.* **51**, 1127-1141 (1972).

³"Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions," ASTM Designation E90-70, American Society of Testing and Materials, Book of Standards, Part 14.

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