Sound Transmission through Partitions*

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Part 1: Diffuse Source Field

The theory originally developed by London and Beranek concerning diffuse source field and transmission between rooms included both direct and reverberant field contributions in the receiving space. The direct field component was calculated by assuming that a receiver was located near the radiating surface. Since a receiver may not be simultaneously close to all radiating surfaces at once, the theory is inconsistent for multiple-path transmission. By taking into account the falloff of the direct field, a formulation can be determined which allows for both self-consistency and an extension of the theory to radiation from buildings to the exterior environment.

0 INTRODUCTION

The problem of sound transmission between spaces separated by a common partition has been of interest for some time. The most common methodology currently in use for this calculation was one given by Beranek [1] for a diffuse or reverberant source field. In a diffuse field the sound energy is usually assumed to be incident on the receiver from all angles with equal probability. Under this assumption,

$$L_p(\text{receiver}) = L_p(\text{diffuse source}) - \text{TL} + 10 \log (S/R + 1/4) \quad (1)$$

where

L_p(receiver)	=	sound pressure level at receiver room, decibels
L_p(diffuse source)	=	diffuse or reverberant sound pressure level in source room, decibels
TL	=	transmission loss of intervening partition, measured in accordance with ASTM E90 test standard, decibels
S	=	radiating surface area of source, square meters
R	=	room constant, square meters.

This equation assumes that the source field is diffuse and that the receiver is in close proximity to the transmitting surface so that the direct field level has not decreased with distance from the radiating panel.

Where the reverberant field dominates, S/R is much greater than 1/4 and the direct field contributor, represented by the one-quarter term, is dropped and the result is reduced to

$$L_p(\text{receiver}) = L_p(\text{diffuse source}) - \text{TL} + 10 \log (S/R) \; . \quad (2)$$

This equation finds common use in the determination of transmission loss as measured between reverberant rooms in laboratory tests. Where multiple transmission paths occur, Beranek defined a transmission coefficient such that

$$\text{TL} = 10 \log (1/\tau) \; . \quad (3)$$

For multiple surfaces the overall transmission loss is

$$\text{TL} = 10 \log \left(\frac{S}{(S_1\tau_1 + S_2\tau_2 + S_3\tau_3 + \cdots + S_n\tau_n)} \right) \quad (4)$$

where τ_n is the transmission coefficient for a particular surface as defined by

$$\tau_n = \text{antilog} (- \text{TL}_n/10) \; . \quad (5)$$

The theory given by Beranek has been compared to measurements originally performed by London [2] at

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the National Bureau of Standards and was found to be in reasonably close agreement.

1 CURRENT DIFFICULTIES

While these formulas have served us well, there are problems with the application of the formulas in some cases. Take, for example, the radiation of sound from a room through a partition into a very absorbent space or into the out-of-doors, where R becomes very large. For this condition neither formula is particularly accurate, unless the observer is close to the radiating panel. In fact, Eq. (2) would predict that no sound would be radiated from a building to the out-of-doors since R is infinite.

A second problem of a more subtle nature occurs when we use Eq. (1). Where there are multiple transmitting surfaces the assumptions used in the derivation of the formula are not met, that is, we cannot be close to all radiating surfaces simultaneously. For example, assume we were to calculate the noise radiated through a low-transmission-loss surface such as a closed window. Say we then calculate, using the composite formula, the level for the addition of more exposed surface, such as a high-transmission-loss wall. We would find that the addition of the more exposed surface would cause the predicted noise level to decrease rather than increase. This is a result that does not agree with experience.

A further problem with Eq. (1) occurs if we do the calculation separately for several surfaces and combine the levels due to transmission through each surface. The answer obtained is different from what we would get if the problem were done with the composite-transmission-loss approach. Thus the technique is not self-consistent.

2 PROPOSED SOLUTION

The reason for these conumdrums is the problem in accounting for the direct field falloff from a surface. The division, for purposes of calculation, of the sound energy into direct and reverberant fields is a well-established principle. The problem is that for a plane surface the integral for incoherent radiation has not been solved in closed form. This problem has been addressed by a number of authors, including Rathe [3], Ellis [4], and more recently Tatge [5]. These authors present approximations or calculated curves to be used in various locations. All of the proposed solutions have difficulties where the source-to-receiver distance goes to zero.

In order to overcome these difficulties, it is useful to return to the original derivation of the equation as follows:

$$L_p(\text{receiver}) = L_p(\text{diffuse source}) - \text{TL} + 10 \log (SQ/4S_r + S/R) \qquad (6)$$

where

S_r = area of sphere or other surface through which sound energy passes at receiver, square meters

Q = directivity of source for specific receiver location, dimensionless.

For a point source S_r is the familiar $4\pi z^2$, where z is the distance between the source and the receiver. While this equation works well for large z, as z approaches 0, the equation blows up. For small z, S_r must approach S so that we retain Eq. (1).

Agreement for both large and small z can be achieved by introducing a term in the distance equation which displaces the source such that the spherical spreading surface area is equal to the radiating surface area when the source-to-receiver distance is zero. Then the source-to-receiver distance z is measured from the radiating surface of the source,

$$L_p(\text{receiver}) = L_p(\text{diffuse source}) - \text{TL} + 10 \log \left[\frac{SQ}{16\pi(z + (SQ/4\pi)^{1/2})^2} + \frac{S}{R} \right] . \qquad (7)$$

The hypothetical center of the radiating source has been displaced by a term $(SQ/4\pi)^{1/2}$, which does a number of useful things for us. When the receiver is close to the wall, z approaches 0 and Eq. (7) reduces to Eq. (1). When there is a highly reverberant receiving room, the direct field contribution is very much smaller than S/R and Eq. (7) becomes Eq. (2). Thus we retain our link to the current formulas in the regions where they are known to be accurate.

Eq. (7) is also useful in that we can employ it for the prediction of radiation from a building to an outdoor environment where R goes to infinity,

$$L_p(\text{receiver}) = L_p(\text{diffuse source}) - \text{TL} + 10 \log \left[\frac{SQ}{16\pi(z + (SQ/4\pi)^{1/2})^2} \right] . \qquad (8)$$

Under free-field conditions, close to a radiating wall, R is infinite and z is equal to 0, so Eq. (7) reduces to

$$L_p(\text{receiver}) = L_p(\text{diffuse source}) - \text{TL} - 6 . \qquad (9)$$

For a free-field receiver where the distance from the surface is large, Eq. (7) becomes

$$L_p(\text{receiver}) = L_p(\text{diffuse source}) - \text{TL} + 10 \log (SQ/16\pi z^2) \qquad (10)$$

or

$$L_p(\text{receiver}) = L_p(\text{diffuse source}) - \text{TL} - 6 + 10 \log (SQ/4\pi z^2) . \qquad (11)$$

Approximate equations can also be obtained for an enclosed receiving space. Where the distance between the source and the receiver results in a receiving area that is large compared to the area of the source, the result is

$$L_p(\text{receiver}) = L_p(\text{diffuse source}) - \text{TL} + 10 \log \left(\frac{SQ}{16\pi z^2} + \frac{S}{R} \right) . \qquad (12)$$

Thus we have a wide range of applicable receiving conditions which can be treated by this approach.

For multiple transmitting surfaces we would no longer use a composite transmission loss. Rather it is necessary to combine the levels from each transmitting surface at the receiver. The methodology thereby avoids the self-consistency problems inherent in the composite transmission loss calculation.

3 OTHER APPLICATIONS

The idea of a displaced center for radiating surfaces can also be used to calculate sound pressure levels from sound power level data. The sound pressure to power level equation is

$$L_p = L_w + 10 \log \left[\frac{Q}{4\pi(z + (SQ/4\pi)^{1/2})^2} + \frac{4}{R} \right] + 0.5 \quad \text{(metric units)} \qquad (13)$$

where L_w is the sound power level of the source in decibels.

As the distance between the source and the receiver is reduced to 0, Eq. (13) reduces to

$$L_p(\text{receiver}) = L_w + 10 \log \left(\frac{1}{S} + \frac{4}{R} \right) + 0.5 \quad \text{(metric units)} \qquad (14)$$

and when the receiver is far from the radiating surface, it reduces to

$$L_p(\text{receiver}) = L_w + 10 \log \left(\frac{Q}{4\pi z^2} + \frac{4}{R} \right) + 0.5 \quad \text{(metric units)} . \qquad (15)$$

4 CONCLUSION

A theory has been presented for the calculation of sound pressure levels from a diffuse sound field through a partition into a receiving space. The receiving space may be enclosed or open. The relationship given in Eq. (7) may be used in a wide variety of applications by changing its internal parameters to suit the conditions. The receiving sound pressure levels include contributions from both the direct sound field radiated from the partition and the reverberant field in the receiving room. The inclusion of this direct-field term overcomes some of the difficulties with current acoustical theory.

Part 2: Direct Source Field

A theory of the transmission of direct field sound into an enclosed space must account for the current diffuse field means of measuring transmission loss. A methodology is set out for calculating the sound level in rooms which accounts for this difference as well as the angular dependence on source position. The methodology can be extended to full and partial line sources.

0 INTRODUCTION

In Part 1 a new relationship was presented for the calculation of sound transmission through partitions for a diffuse or reverberant source field. For a direct source field the behavior of the transmission loss is somewhat different. A direct field consists of a plane or nearly plane wave which proceeds directly from the source to the transmitting surface. The energy density and thus the relationship between sound pressure levels and sound intensity levels for a plane wave differs by 6 dB from the relationship for a diffuse field [6]. The transmission loss of a surface is also dependent on the angle of incidence, and this must be accounted for in any comprehensive theory.

1 BACKGROUND

For plane waves the power transmitted through a surface is simply related to the intensity incident on the surface,

$$W = IS \cos\theta\, \tau(\theta) \qquad (16)$$

where

- W = power transmitted through a surface, watts
- I = direct field intensity impacting the surface, watts per square meter
- θ = angle of incidence with normal to surface, degrees
- $\tau(\theta)$ = transmission coefficient of surface for angle θ, dimensionless

For a single exposed surface and an interior observer, Eq. (16) may be plugged into Eq. (13) of Part 1 to obtain

$$L_p(\text{receiver}) = L_p(\text{direct source}) - \text{TL}(\theta) + 10 \log (4 \cos\theta) + 10 \log\left[\frac{SQ}{16\pi(z + (SQ/4\pi)^{1/2})^2} + \frac{S}{R}\right] \qquad (17)$$

where

- L_p(direct source) = direct field sound pressure level measured near but in the absence of reflections from transmitting surface, decibels
- TL(θ) = direct field transmission loss of a partition for a given angle of incidence θ, decibels.

Let us define a receiver correction C such that

$$C = 10 \log\left[\frac{SQ}{16\pi(z + (SQ/4\pi)^{1/2})^2} + \frac{S}{R}\right] . \qquad (18)$$

Then, for normal incidence,

$$L_p(\text{receiver}) = L_p(\text{direct source}) - \text{TL}(\theta = 0) + C + 6 . \qquad (19)$$

Note that if $z = 0$ and TL(θ) = 0 at the center of an open window and if $R = \infty$, then

$$L_p(\text{receiver}) = L_p(\text{direct source})$$

as it should.

2 TRANSMISSION LOSS

Transmission loss measurements are performed under diffuse field conditions in highly reverberant laboratory test rooms. On the source side, by control of the absorption in the room and the number and orientation of the loudspeakers, a diffuse (reverberant) field is achieved at the test partition. Under these conditions, one-quarter of the measured sound pressure level contributes to the transmitted power and Eq. (2) is valid,

$$L_p(\text{receiver}) = L_p(\text{diffuse source}) - \text{TL} + 10 \log (S/R) . \qquad (2)$$

The bulk of transmission loss data have been measured in this manner. There is some difficulty, however, in applying these data to direct source field calculations since there is no specific angular dependence in the diffuse field laboratory data.

This leads to an inquiry into the nature of the angular dependence of the transmission loss behavior of partitions. A number of theoretical derivations of this behavior have been developed. Angular dependencies are varied and complex. The simplest is the traditional mass law which, according to Ver and Holmer [7], is

$$\text{TL}(\theta) = 10 \log [1 + (\omega\rho_s \cos\theta/2\rho c)^2] \qquad (20)$$

where

- ω = circular frequency, radians per second
- ρ_s = surface mass density of panel, kilograms per square meter
- ρ = density of air, kilograms per cubic meter
- c = velocity of sound in air, meters per second.

This equation is normally integrated for values of θ between 0° and about 80° to obtain agreement with measured results for laboratory tests. The TL data are generally found to be some 5 dB below the TL(θ = 0) data. For purposes of this report the angular dependence of all partitions is taken to be the mass law dependence shown above. This does not preclude the use of actual measured TL data, but only means that this angular dependence is assumed. For walls of normal density $\omega\rho_s \cos\theta/2\rho c >> 1$ for angles less than 80°, so that

$$\text{TL}(\theta) = \text{TL}(\theta = 0) + 20 \log \cos\theta . \qquad (21)$$

Substituting in Eq. (21)

$$\text{TL}(\theta = 0) - \text{TL} = 5 \qquad (22)$$

which was determined empirically from laboratory tests, one obtains

$$\text{TL}(\theta) = \text{TL} + 5 + 20 \log \cos\theta . \qquad (23)$$

Note that while this equation is used in subsequent calculations, if TL(θ) = 0, then we must revert to using Eq. (2) to obtain a correct result.

3 PRACTICAL APPLICATIONS

The individual components are now available to permit assessing the interior noise level. The basic formula is

$$L_p(\text{receiver}) = L_p(\text{direct source}) - \mathrm{TL} - \Delta\mathrm{TL} + C + G \quad (24)$$

where

ΔTL = correction for shielding plus difference between G factor for primary surface and surface of interest, decibels

G = geometrical factor, which includes orientation of source relative to primary surface, plus a correction for difference between normal incidence transmission loss values and field data, decibels,

$$G = 10 \log (4 \cos \theta) + (-5 - 20 \log \cos \theta) \quad (25)$$

$$= 10 \log (1.26/\cos \theta) \quad . \quad (26)$$

4 POINT SOURCE—NORMAL INCIDENCE

In the simplest case for normal incidence and one exposed surface,

$$L_p(\text{receiver}) = L_p(\text{direct source}) - \mathrm{TL} + C + 1 \quad (27)$$

or the more familiar

$$L_p(\text{receiver}) = L_p(\text{direct source}) - \mathrm{TL}(\theta = 0) + C + 6 \; . \quad (28)$$

This is the same form as Eq. (A3) in ASTM E336 for normal incidence.

5 POINT SOURCE—NONNORMAL INCIDENCE

For other angles of incidence, the value of G may be calculated as follows:

	Angle θ, degrees								
	0	10	20	30	40	50	60	70	80
G factor, dB	1.0	1.1	1.3	1.6	2.2	2.9	4.0	5.7	8.6

It is common practice not to include angles above 80°.

6 LINE SOURCE—EXPOSED SURFACE PARALLEL TO IT

The line source G factor for one exposed surface may be determined by energy averaging G values over all values of θ. The G factors at 0° and 80° are single counted while the other angles are double counted. The result for a line source parallel to the exposed surface is

$$G = 3.6 - 10 \log \cos \phi \quad (29)$$

Table 1. Ground level line source ΔTL values (Front wall parallel to source, $\phi = 0$)

Surface type	ΔTL, dB
Front wall	0
Sidewall	+3
Flat roof	+6
Pitched roof	+0–6 (depending on angle of roof)
Rear wall	+10–15

where ϕ is the angle between the normal to the surface and the normal to the line source (maximum value 45°).

7 ΔTL

It should be noted that for surfaces perpendicular to a line source, the G value is theoretically the same as that for a parallel surface. The side of a building, however, will be exposed to a sound pressure level which is lower by about 3 dB than the front surface due to the self-shielding by the building. Where multiple surfaces are involved, a shielding constant ΔTL can be introduced for convenience. Where there are complicated geometries, both shielding and G factor have to be adjusted for an individual surface. Working values of ΔTL are shown in Table 1. The G factor is taken to be constant based on the primary exposed surface.

The difficulty in accurately assessing the G factor and the ΔTL for all geometries is apparent. For odd orientations there is always a tradeoff between shielding and θ dependence. For practical calculations shielding is usually slightly more important than the G factor. If the primary surface is not parallel to the roadway within 30° or so, it makes little difference in the G factor while making about a 1-dB difference in the ΔTL value for the primary surface. In general the two factors offset one another. For aircraft and other elevated sources both roofs and sidewalls are generally considered to have a ΔTL of zero.

8 CONCLUSION

A theory has been presented for sound transmission from a direct source field through a partition into a receiving space. The fundamental relationship is that shown in Eq. (17). Since the transmission loss behavior with angle is not generally measured, an approximation for purposes of calculation convenience has been given as Eq. (23). This results in the practical methodology shown in Eq. (24). This permits the calculation of sound levels from both diffuse and direct source fields. For both theories, sound levels from multiple transmitting surfaces are calculated separately and combined in the receiving space.

If both diffuse and direct sound fields are impinging upon a partition, the levels due to each of these fields would have to be calculated separately.

9 REFERENCES

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