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MEASURED AND CALCULATED TRANSMISSION LOSSES OF SOUND WAVES THROUGH A HELIUM LAYER

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16. Abstract

An experiment was performed to measure the transmission losses of sound waves traversing an impedance layer. The sound emanated from a point source and the impedance layer was created by a low-speed helium jet. The transmission losses measured were of the order of 12 dB for frequencies of the source between 4 and 12 kHz. These losses are greater than those predicted from analysis when the observer angle is less than about 35°, but less than those predicted for larger observer angles. The experimental results indicate that appreciable noise reductions can be realized for an observer shielded by an impedance layer, irrespective of his position relative to the source of sound.

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MEASURED AND CALCULATED TRANSMISSION LOSSES OF SOUND WAVES THROUGH A HELIUM LAYER

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SUMMARY

An experiment was performed to measure the transmission losses of sound waves traversing an impedance layer. The sound emanated from a point source and the impedance layer was created by a low-speed helium jet. The transmission losses measured were of the order of 12 dB for frequencies of the source between 4 and 12 kHz. These losses are greater than those predicted from analysis when the observer angle is less than about 35°, but less than those predicted for larger observer angles. The experimental results indicate that appreciable noise reductions can be realized for an observer shielded by an impedance layer, irrespective of his position relative to the source of sound.

INTRODUCTION

Concern over reducing the effects of jet noise has led to interest in shielding the observer from the noise by a layer of gas in which the acoustic impedance differs from that of the region in which the noise is generated. Jones (ref. 1) compared the power spectra of a 0.019-m-diameter (0.75 in.) jet with and without a surrounding shroud of hot gas. He found reductions in the measured noise under some conditions due to the presence of the high-temperature shroud. However, since the noise sources in a jet are unknown, there is difficulty in comparing the experimental results with theoretical results. Hence, it was decided to investigate shielding by using pure tones emitted by a point source so that a comparison between experimental and theoretical results could be made.

It was desired to obtain the largest possible experimental reductions in sound level for a given geometry. Analyses (refs. 2 to 6) for the transmission of plane waves through an impedance layer show that the properties of the media which affect the magnitude of the reduction in sound level through the layer are the speed-of-sound ratio and the impedance ratio between the two regions. Since the speed of sound in helium is larger than that in any other gas except hydrogen, and almost three times that in air, a jet of helium was used to create the impedance layer.

In this report, the theoretical solution for the transmission of spherical sound waves through an impedance layer is derived. Experimental results for the transmission

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loss of spherical waves emanating from a point source and traversing a helium layer are presented and compared with theoretical results.

SYMBOLS

Measurements and calculations were made in the U.S. Customary Units. They are presented herein in the International System of Units (SI) with the equivalent values in the U.S. Customary Units given parenthetically.

A	parameter defined by equation (3)
a,b	coefficients used in equations (A5), N (lbf)
c	speed of sound, m/sec (fps)
d	thickness of impedance layer, m (in.)
J_0	Bessel function of zeroth order
k	wave number, ω/c, m^{-1} (in^{-1})
k_x,k_y	wave number projections on X and Y axes, respectively, m^{-1} (in^{-1})
L	integral defined by equation (A16)
P	time-dependent acoustic pressure, Pa (psi)
$\bar{P}$	Fourier transform of acoustic pressure, N (lbf)
p	time-independent acoustic pressure, Pa (psi)
p_o	time-independent acoustic pressure without impedance layer, Pa (psi)

$R = \left(x^2 + y^2 + z^2\right)^{1/2}$, m (in.)

$r = \left(x^2 + y^2\right)^{1/2}$, m (in.)

SPL	sound pressure level, dB (re. 2×10^{-5} Pa)
t	time, sec

$\vec{V}$ acoustic velocity, m/sec (fps)

x,y,z Cartesian coordinates, m (in.)

Z normal acoustic impedance, kg/m^2-sec (lbm/ft^2-sec)

z_1,z_2 z-coordinates of impedance interfaces, m (in.)

ΔSPL decrease in SPL due to presence of impedance layer, dB

α, ϕ angles defined by equations (A10), rad

β parameter defined by equation (2)

δ delta function, m^{-1} (in^{-1})

ζ z-component of wave number, m^{-1} (in^{-1}) (see eqs. (A6))

η integration variable defined by equation (A13)

θ_o incidence angle of plane wave, rad

ν observer angle, rad (see fig. 2)

ξ wave number component defined by equations (A10), m^{-1} (in^{-1})

ρ density, kg/m^3 (lbm/ft^3)

σ strength of point source, N/m (lbf/in.)

ω angular frequency, sec^{-1}

Subscripts:

o,i surroundings and impedance layer, respectively (used with c, p, k, and ζ)

r ratio of value in impedance layer to value in surroundings (used with c and Z)

1,2,3,4 four regions of figure 6 (used with p, $\overline{P}$, a, and b)

EXPERIMENTAL APPARATUS

The experiment was conducted in the Langley anechoic noise facility (ref. 7). The tests consisted of a point source of sound which generated waves that traversed an impedance layer created by a low-speed helium jet exhausting through a rectangular nozzle. A photograph of these components is shown in figure 1 along with a schematic of the refraction phenomenon. The nozzle and source were wrapped in 0.025-m-thick (1 in.) foam to minimize reflections. The physical positions of the various components during the experiment are shown in figure 2.

Point Source

The source consisted of two drivers enclosed in an insulated container with a 0.762-m (30 in.) long, 0.003-m (1/8 in.) I.D. steel tube protruding from the container. This arrangement produced spherical sound waves emanating from the end of the tube at the frequency at which the drivers were excited. The point source is very similar to that described in reference 8.

The symmetry of the sound field produced by the point source was examined by sweeping a microphone in a circular arc of 90^{o} in a vertical plane around the end of the tube. (See fig. 2.) This was done at different distances from the source at frequencies of 2, 4, and 12 kHz. At distances less than 0.305 m (12 in.) from the source, the directivity showed an omnidirectional pattern. However, at farther distances from the source, asymmetry in the directivity became apparent. This asymmetry increased with the sweep radius of the microphone, implying that reflections in the room were larger than anticipated.

Helium Jet

The impedance layer was created by a helium jet exhausting through a 0.102-m (4 in.) by 0.711-m (28 in.) rectangular nozzle. Four layers of 0.025-m-thick (1 in.) honeycomb were positioned in the nozzle to ensure that the helium jet filled the exit plane of the nozzle. Since the velocity of the jet was to be maintained at a very small value, a standard impact probe could not be used to measure it. Instead a 0.025-m-diameter (1 in.) propeller was placed at the nozzle exit. The rotation of the propeller was measured by a photocell which was calibrated to give the velocity of the jet. The exit velocity was maintained at 1.219 m/sec (4 fps) during the experiment. A gas analyzer was used to ensure that the helium exhausted out the ceiling port in the anechoic chamber and did not contaminate the region surrounding the jet.

Instrumentation

Sound pressure levels (SPL) were measured with a 0.013-m-diameter (1/2 in.) condenser microphone which was capable of a 1.473-m (58 in.) vertical traverse as shown in figure 2. All measurements were recorded on tape and subsequently analyzed by using a 10-Hz narrow-band filter and a graphic level recorder. The overall frequency response of the entire recording system was flat within ±2 dB from 500 Hz to 40 000 Hz.

DISCUSSION OF RESULTS

Noise Measurements

The experiment was performed at frequencies of the source from 2 to 12 kHz. At frequencies below 1500 Hz the sound pressure level of the helium jet system was greater than that of the source. However, the system noise fell off rapidly at higher frequencies, whereas the output of the source was relatively constant at these higher frequencies.

With the source activated, the microphone was set in motion at a constant speed of 0.016 m/sec (38 ipm). Vertical microphone traverses were made to measure the SPL at frequencies of 2, 4, 6, 8, 10, and 12 kHz with and without the helium jet. An additional microphone traverse was made with the source deactivated to determine the noise level of the helium system alone.

The results of these three microphone sweeps filtered at a center frequency of 6 kHz and a bandwidth of 10 Hz are shown in figure 3. The results are plotted as a function of $\tan \nu$, where ν is the observer angle shown in figure 2. The top trace gives the SPL obtained without the helium jet. The dash-line curve superimposed on this trace is the variation predicted from the R^2 decay law for spherical waves. The deviations about this curve show the asymmetry of the sound field mentioned previously.

To determine the effect of the moving microphone, the SPL was measured with the source activated and the microphone at a fixed position. This level was equal to the level obtained at the same position with the microphone in motion, which indicates that this motion had no effect on the measurements.

It was also found that there was no time variation in the SPL recorded with the source emitting and the microphone fixed. However, with the jet activated the level fluctuated by about ±3 dB; this indicated that the transmission loss through the jet was time dependent. These fluctuations may be due to the nature of the turbulent mixing of the low-speed helium jet with the surrounding air. Due to this time dependence and to the apparent asymmetry of the source, analysis of the results was made by dividing the range of the microphone sweep into six parts. A mean sound pressure level was obtained for each of these six parts by averaging the levels measured during this portion of the microphone sweep. The transmission loss through the helium layer for each part was then computed as the difference between the mean sound pressure levels with and without the helium jet, corrected for the noise level of the jet system. This correction was made by the standard method of combining uncorrelated noise sources and amounted to less than 1 dB for all frequencies above 2 kHz.

The reductions in sound pressure level ΔSPL through the helium layer are shown in figure 4 plotted against the tangent of the observer angle. Also shown are the least-squares straight-line fits through the data. The results indicate an increase in ΔSPL with both frequency and observer angle. Reductions are between 7 and 16 dB for frequencies from 4 to 12 kHz.

Analytical Results

Previous analyses for the transmission of sound through an impedance layer have been performed only for plane waves (refs. 2 to 6). Since the experiment uses a point source of sound emitting spherical rather than plane waves, the solution for spherical waves is derived in the appendix and the two results are compared in this section.

The transmission coefficient for a plane wave of angular frequency ω incident at an angle θ_o to a stationary homogeneous layer of thickness d (fig. 5) is given by Brekhovskikh (ref. 2, p. 48). The SPL reduction in decibels can be represented as

$$\Delta SPL = 10 \log\left[1 + \left(\frac{1 - \beta^2}{2\beta} \sin A\beta\right)^2\right] \tag{1}$$

where

$$\beta = \frac{\sqrt{1 - c_r^2 \sin^2\theta_o}}{Z_r \cos \theta_o} \tag{2}$$

$$A = k_i d Z_r \cos \theta_o \tag{3}$$

$$c_r = \frac{c_i}{c_o} \tag{4}$$

$$Z_r = \frac{\rho_i c_i}{\rho_o c_o} \tag{5}$$

$$k_i = \frac{\omega}{c_i} \tag{6}$$

ρ is the density, c is the speed of sound, and the subscripts i and o refer to the impedance layer and surroundings, respectively.

The pressure field opposite an impedance layer due to a point source (fig. 6) is computed in the appendix by expanding the spherical waves into plane waves through a double Fourier integral. The result, given by equation (A15), yields a SPL reduction through the layer of

$$\Delta SPL = -10 \log\left[16k_i^2\left(r^2 + z^2\right)c_r^2 Z_r^2 LL^*\right] \tag{7}$$

where the integral L is given by equation (A16), and L^* is its complex conjugate. This integral was evaluated by approximating the zeros of the real part of the integrand and using a 10-point Gaussian integration scheme between successive zeros. This resulted in at most two zeros per integration and ensured negligible error in the evaluation of the integral.

To compare plane and spherical wave results, it is noted that the angle of incidence θ_o for the plane wave in figure 5 is roughly comparable to the observer angle ν for the spherical wave in figure 6. Hence, the calculated reduction in SPL is plotted against $\tan \theta_o$ for the plane wave in figure 7 and against $\tan \nu$ for the point source in figure 8. In both figures, results are shown for the conditions of the experiment, namely:

$$Z_r = 0.406$$

$$c_r = 2.935$$

$$c_o = 347 \text{ m/sec} \quad (1137 \text{ fps})$$

$$d = 0.102 \text{ m} \quad (4 \text{ in.})$$

$$z = 1.092 \text{ m} \quad (43 \text{ in.})$$

Figure 7 shows that the transmission loss of a plane wave is small at all frequencies until $\tan \theta_o$ reaches 0.362, which corresponds to the critical angle of incidence, $\sin^{-1}\left(1/c_r\right) = 19.9^\circ$. At this point, β in equation (1) becomes imaginary and the transmission loss begins to increase rapidly. Similar low SPL reductions are obtained for spherical waves at small observer angles in figure 8. However, the plane wave solution predicts an increase in ΔSPL with an increase in frequency at large incidence angles; whereas, the spherical wave solution shows little effect of frequency between 6 and 12 kHz at large observer angles.

To determine the effects of the motion and spreading of the helium jet, two comparisons were made. Differences due to the motion of the helium were examined by using the plane wave solution for a homogeneous layer moving at a uniform low subsonic Mach number (ref. 4). It was found that the transmission loss is larger and the critical angle of incidence is smaller than those of the stationary homogeneous layer. However, the differences are small and the results of the two analyses agree qualitatively. The effect of spreading was investigated by considering the transmission of a plane wave through a layer having a speed-of-sound profile symmetrically distributed about the center of the layer (ref. 2, p. 185). This particular profile reduces the wave equation to a hypergeometric equation. The parameters of the profile were chosen so that the energy associated with this speed-of-sound distribution was equivalent to the energy associated with a homogeneous layer. Good qualitative agreement was again found between this analysis and that for the stationary layer of constant thickness.

It appears from these comparisons that the mean motion of the helium jet and its spreading by entrainment of the quiescent surrounding air should not appreciably affect the nature of the experimental results.

Comparison of Experiment and Analysis

The reductions in sound pressure level through the helium layer as determined from the spherical wave solution and from experiment are given in figure 9 for frequencies from 4 to 12 kHz. Experimental results show that ΔSPL increases with observer angle at a smaller rate than that obtained theoretically. The measured transmission loss is greater than that predicted when the observer angle is less than about 35° ($\tan \nu = 0.7$), but less than that predicted for larger observer angles.

CONCLUDING REMARKS

Sound pressure level reductions of the order of 12 dB were obtained for high-frequency sound (4 to 12 kHz) emanating from a point source and traversing an impedance layer. The layer was created by a low-speed helium jet exhausting through a rectangular nozzle. The reductions measured in this experiment are greater than those predicted from analysis when the observer angle is less than about 35°, but less than those predicted for larger observer angles. The experimental results indicate that appreciable noise reductions can be realized for an observer shielded by an impedance layer, irrespective of his position relative to the source of sound.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., April 13, 1973.

APPENDIX

DETERMINATION OF PRESSURE FIELD FROM A SPHERICAL WAVE PASSING THROUGH AN IMPEDANCE LAYER

The steady-state solution for the acoustic pressure field due to a monochromatic point source of angular frequency ω located at the origin in figure 6 is

$$P(x,y,z,t) = p(x,y,z)e^{-i\omega t} \tag{A1}$$

where p satisfies

$$\left[\nabla^2 + k^2(z)\right]p(x,y,z) = -4\pi\sigma\ \delta(x)\ \delta(y)\ \delta(z) \tag{A2}$$

σ is related to the strength of the point source, and $k(z) = \frac{\omega}{c(z)}$. Introducing the Fourier transformation

$$p(x,y,z) = \iint_{-\infty}^{\infty} dk_x\ dk_y\ \overline{P}\left(z;k_x,k_y\right)e^{i\left(k_x x+k_y y\right)} \tag{A3}$$

into equation (A2) and performing the usual operations results in

$$\left[\frac{d^2}{dz^2} + k^2(z) - k_x{}^2 - k_y{}^2\right]\overline{P}\left(z;k_x,k_y\right) = -\frac{\sigma}{\pi}\ \delta(z) \tag{A4}$$

The solution of equation (A4) can be represented in each of the four regions specified in figure 6 as

$$\left.\begin{aligned}
\overline{P}_1 &= a_1e^{i\zeta_o z} + b_1e^{-i\zeta_o z} &\quad& (-\infty < z \leq 0)\\
\overline{P}_2 &= a_2e^{i\zeta_o z} + b_2e^{-i\zeta_o z} && (0 \leq z \leq z_1)\\
\overline{P}_3 &= a_3e^{i\zeta_i z} + b_3e^{-i\zeta_i z} && (z_1 \leq z \leq z_2)\\
\overline{P}_4 &= a_4e^{i\zeta_o z} + b_4e^{-i\zeta_o z} && (z_2 \leq z < \infty)
\end{aligned}\right\} \tag{A5}$$

where

$$\left.\begin{aligned} \zeta_o &= \left[\left(\frac{\omega}{c_o}\right)^2 - k_x^2 - k_y^2\right]^{1/2} \\ \zeta_i &= \left[\left(\frac{\omega}{c_i}\right)^2 - k_x^2 - k_y^2\right]^{1/2} \end{aligned}\right\} \tag{A6}$$

The eight coefficients in equations (A5) are obtained from the following conditions:

(1) and (2) The solution must consist of outgoing waves only as $|z| \rightarrow \infty$. Hence, $a_1 = b_4 = 0$.

(3), (4), and (5) The acoustic pressure must be continuous; this results in continuity of $\overline{P}$ at $z = 0$, z_1, and z_2.

(6) and (7) The normal component of acoustic velocity must be continuous across the impedance interfaces z_1 and z_2. Since

$$\vec{V}(x,y,z) = \frac{\nabla p(x,y,z)}{i\omega\rho}$$

then $\frac{1}{\rho}\frac{d\overline{P}}{dz}$ is continuous at z_1 and z_2.

(8) Integration of equation (A4) across $z = 0$ yields

$$\frac{d\overline{P}}{dz}\left(0^+;k_x,k_y\right) - \frac{d\overline{P}}{dz}\left(0^-;k_y,k_y\right) = -\frac{\sigma}{\pi} \tag{A7}$$

The result for region 4 is obtained after some simple but lengthy calculations as

$$\overline{P}_4 = \frac{2i\sigma c_r Z_r}{\pi} \frac{\zeta_i e^{i\zeta_o(z-d)}}{\left(c_r\zeta_i + Z_r\zeta_o\right)^2 e^{-i\zeta_i d} - \left(c_r\zeta_i - Z_r\zeta_o\right)^2 e^{i\zeta_i d}} \tag{A8}$$

where

$$\left.\begin{aligned} c_r &= \frac{c_i}{c_o} \\ Z_r &= \frac{\rho_i c_i}{\rho_o c_o} \\ d &= z_2 - z_1 \end{aligned}\right\} \tag{A9}$$

The acoustic pressure in region 4 is now obtained from equation (A3). By introducing the transformations

$$\left.\begin{aligned} k_x &= \xi \cos \phi \qquad & x &= r \cos \alpha \\ k_y &= \xi \sin \phi \qquad & y &= r \sin \alpha \end{aligned}\right\} \tag{A10}$$

and recalling that

$$\int_0^{2\pi} e^{ir\xi\cos(\phi - \alpha)} d\phi = 2\pi J_0(\xi r)$$

the acoustic pressure reduces to

$$p_4(r,z) = 4i\sigma c_r Z_r \int_0^{\infty} \frac{J_0(r\xi)\sqrt{k_i^2 - \xi^2}\, e^{i\sqrt{k_o^2 - \xi^2}(z-d)}\, \xi\, d\xi}{\left(c_r\sqrt{k_i^2 - \xi^2} + Z_r\sqrt{k_o^2 - \xi^2}\right)^2 e^{-i\sqrt{k_i^2 - \xi^2}d} - \left(c_r\sqrt{k_i^2 - \xi^2} - Z_r\sqrt{k_o^2 - \xi^2}\right)^2 e^{i\sqrt{k_i^2 - \xi^2}d}} \tag{A11}$$

The pressure field without the impedance layer is obtained by setting $d = 0$ in equation (A11). Thus,

$$p_o(r,z) = i\sigma \int_0^{\infty} \frac{J_0(r\xi) e^{i\sqrt{k_o^2 - \xi^2}z}\, \xi\, d\xi}{\sqrt{k_o^2 - \xi^2}} = \sigma \frac{e^{ik_o\sqrt{r^2 + z^2}}}{\sqrt{r^2 + z^2}} \tag{A12}$$

as expected.

By introducing

$$\eta = \frac{\xi}{k_i} \tag{A13}$$

and noting that

$$\frac{k_o}{k_i} = \frac{c_i}{c_o} = c_r \tag{A14}$$

equation (A11) becomes

$$p_4(r,z) = 4i\sigma c_r Z_r k_i L\left(k_i r, k_i d, k_i z, c_r, Z_r\right) \tag{A15}$$

where

$$L = \int_0^\infty \frac{\sqrt{1 - \eta^2}\, J_0\left(k_i r \eta\right) e^{ik_i(z-d)\sqrt{c_r^2 - \eta^2}}\, \eta\, d\eta}{\left(c_r\sqrt{1 - \eta^2} + Z_r\sqrt{c_r^2 - \eta^2}\right)^2 e^{-ik_i d\sqrt{1-\eta^2}} - \left(c_r\sqrt{1 - \eta^2} - Z_r\sqrt{c_r^2 - \eta^2}\right)^2 e^{ik_i d\sqrt{1-\eta^2}}} \tag{A16}$$

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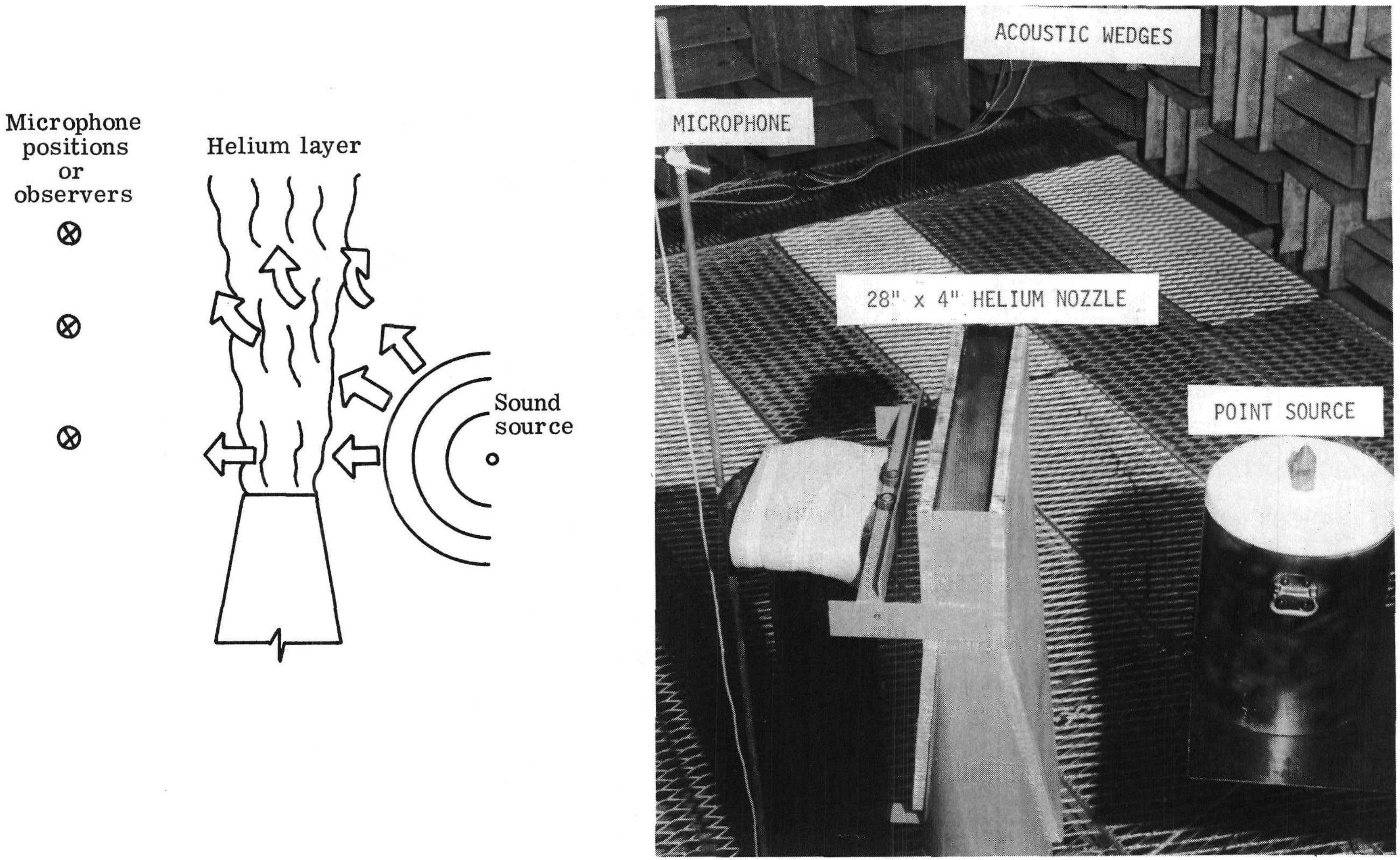

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Figure 1.- Schematic of refraction phenomenon and photograph of experimental components in the Langley anechoic noise facility.

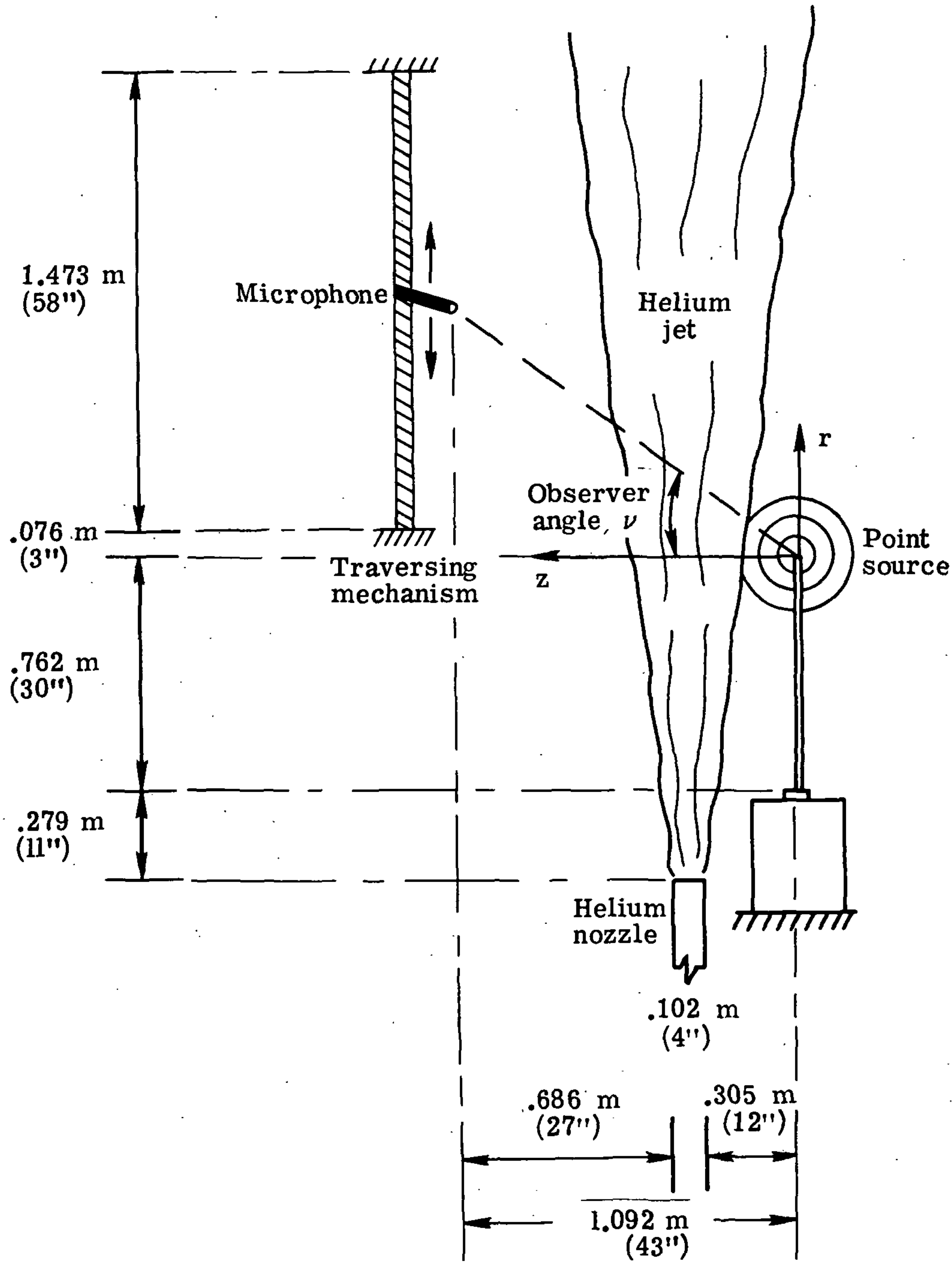

Figure 2.- Schematic side view of experiment.

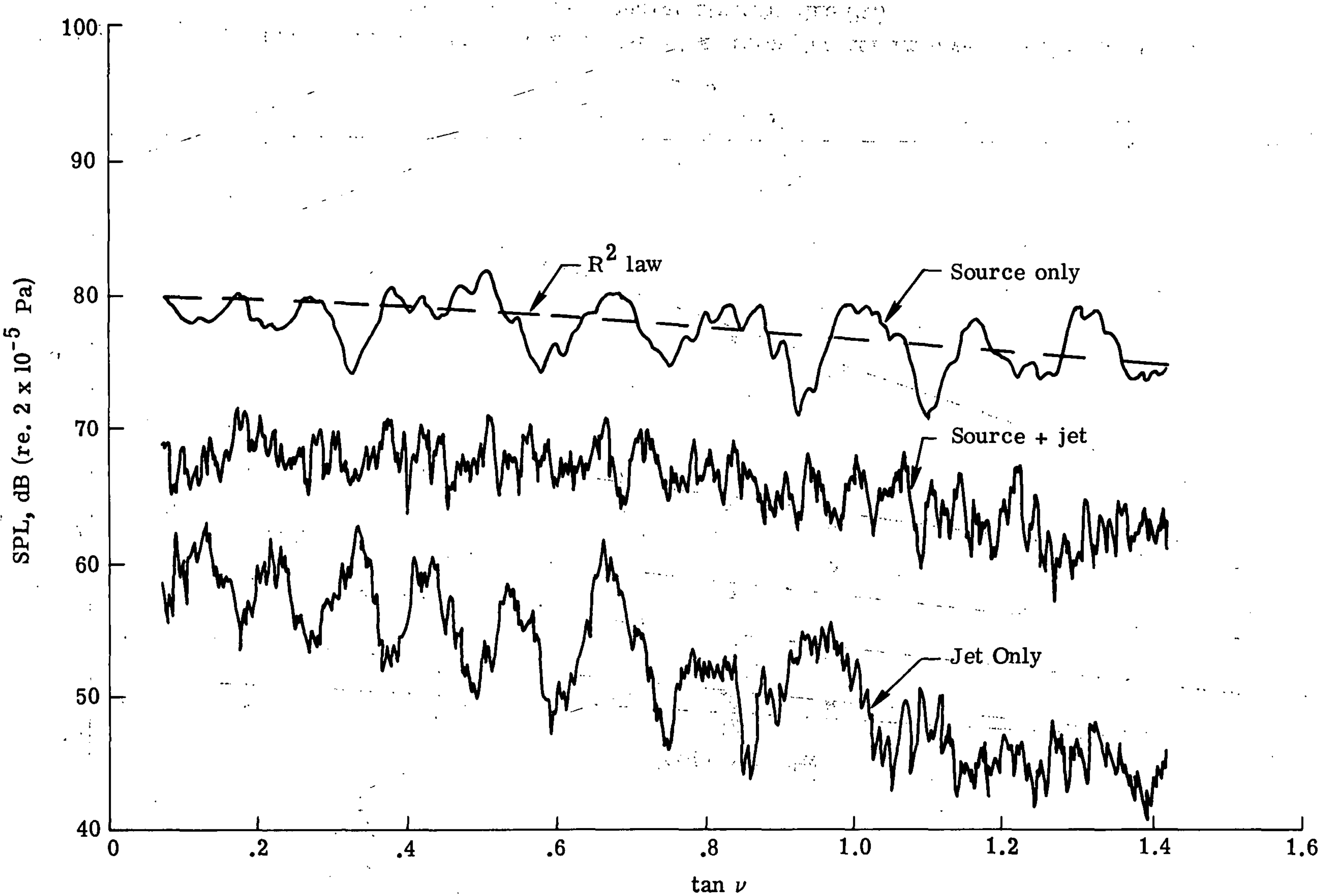

Figure 3.- Results of microphone sweeps filtered at a center frequency of 6 kHz.

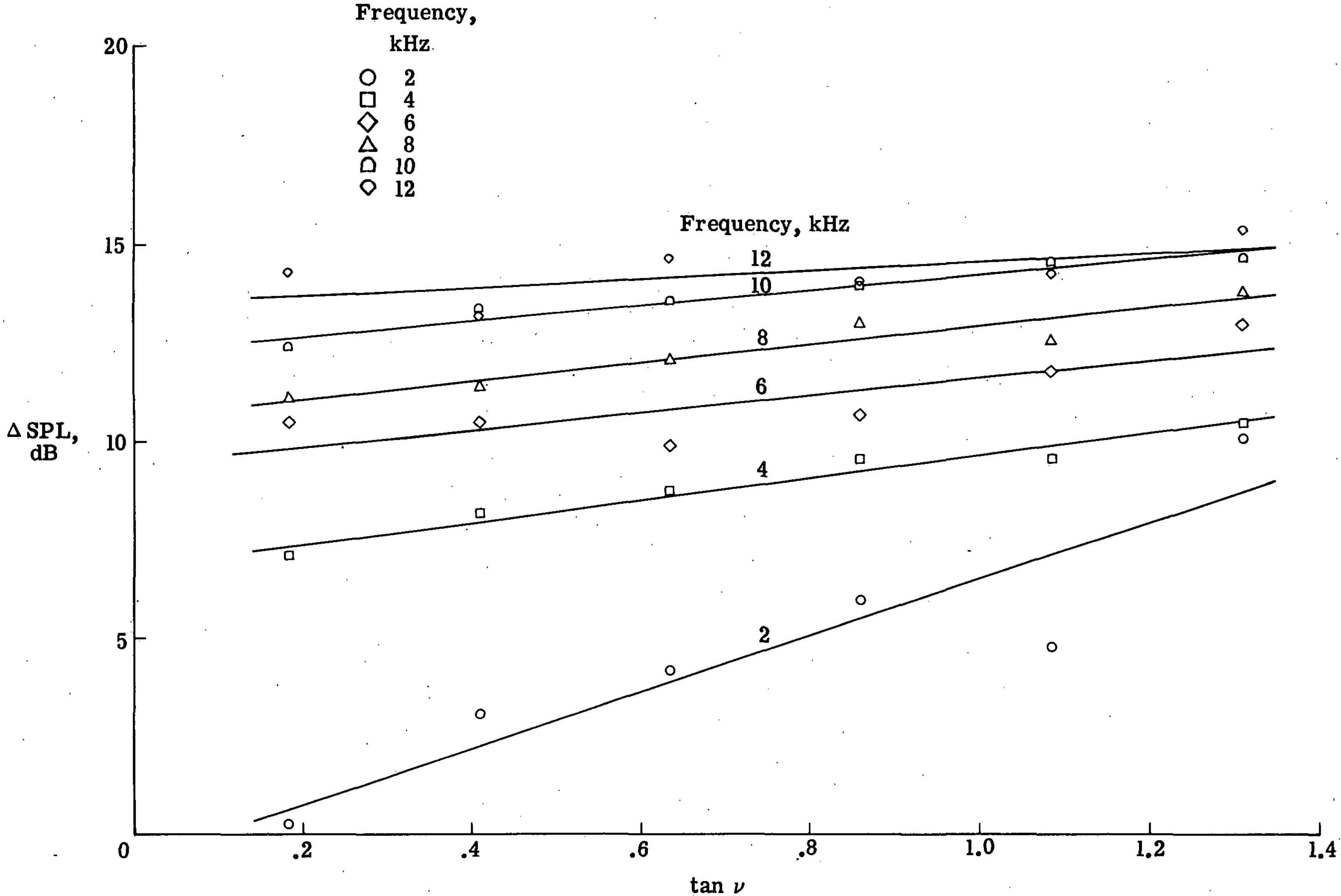

Figure 4.- Experimental results for the transmission loss through a helium layer. (Solid line through symbols is least-squares straight-line fit.)

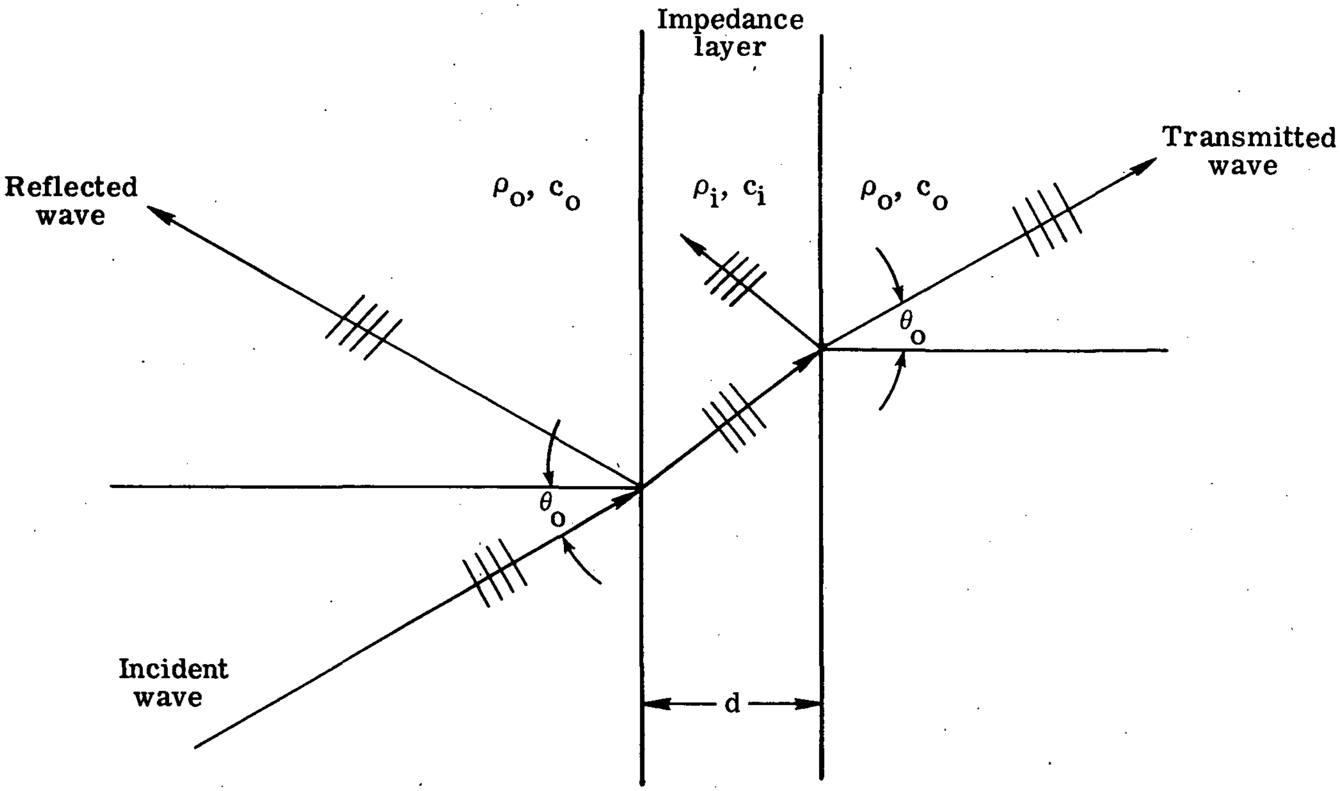

Figure 5.- Transmission of plane waves through an impedance layer.

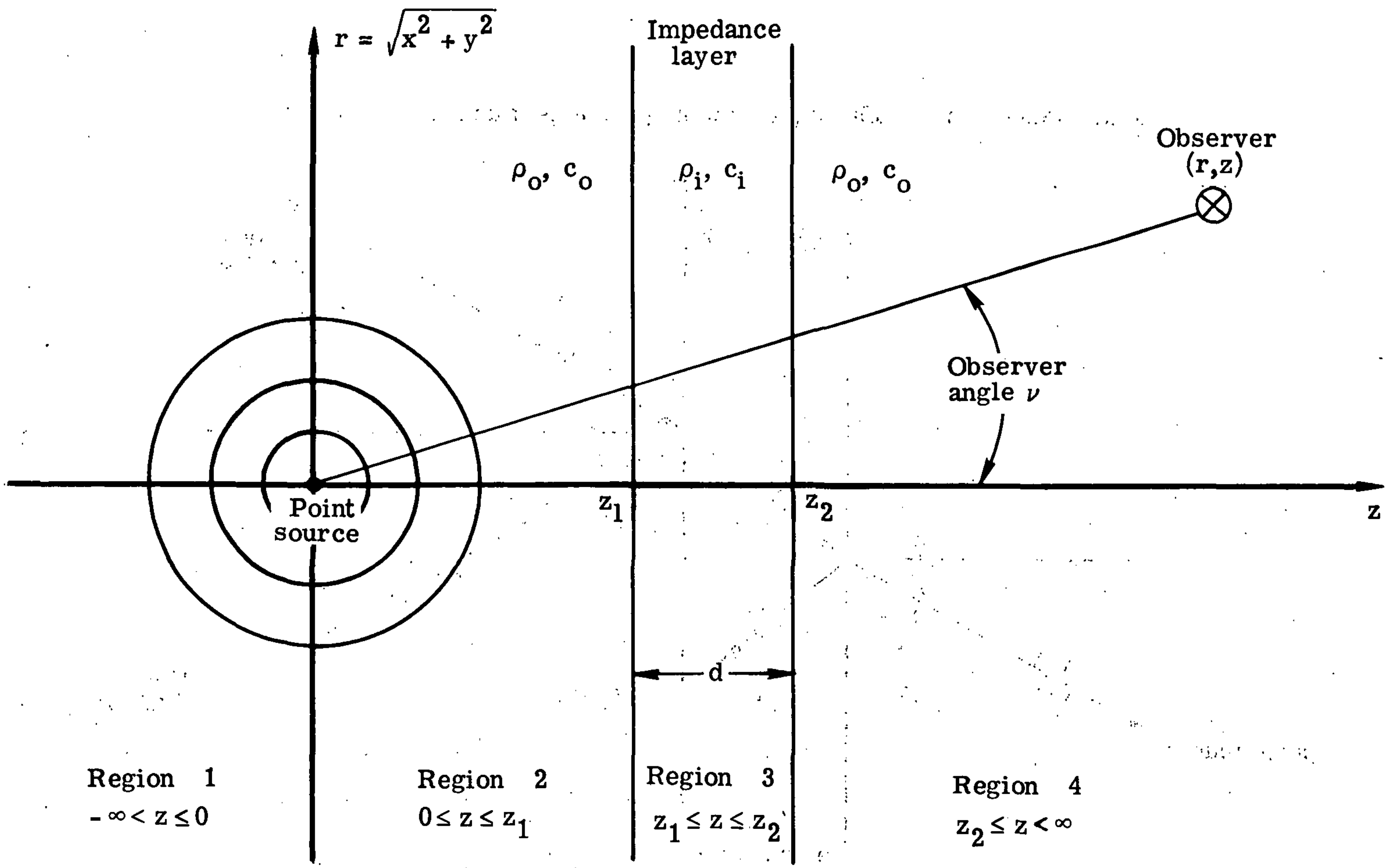

Figure 6.- Transmission of spherical waves through an impedance layer.

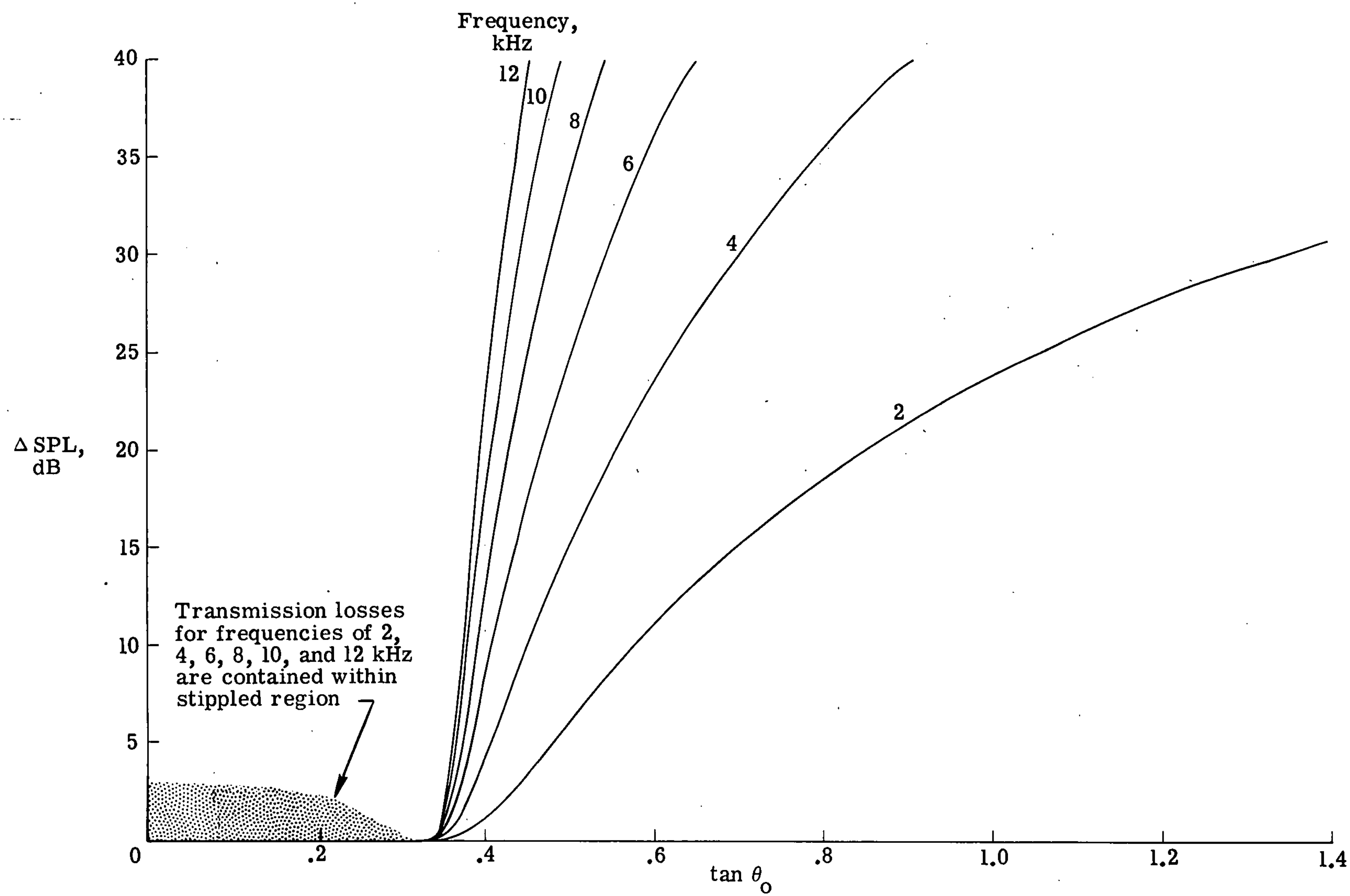

Figure 7.- Calculated plane wave transmission loss through a helium layer.

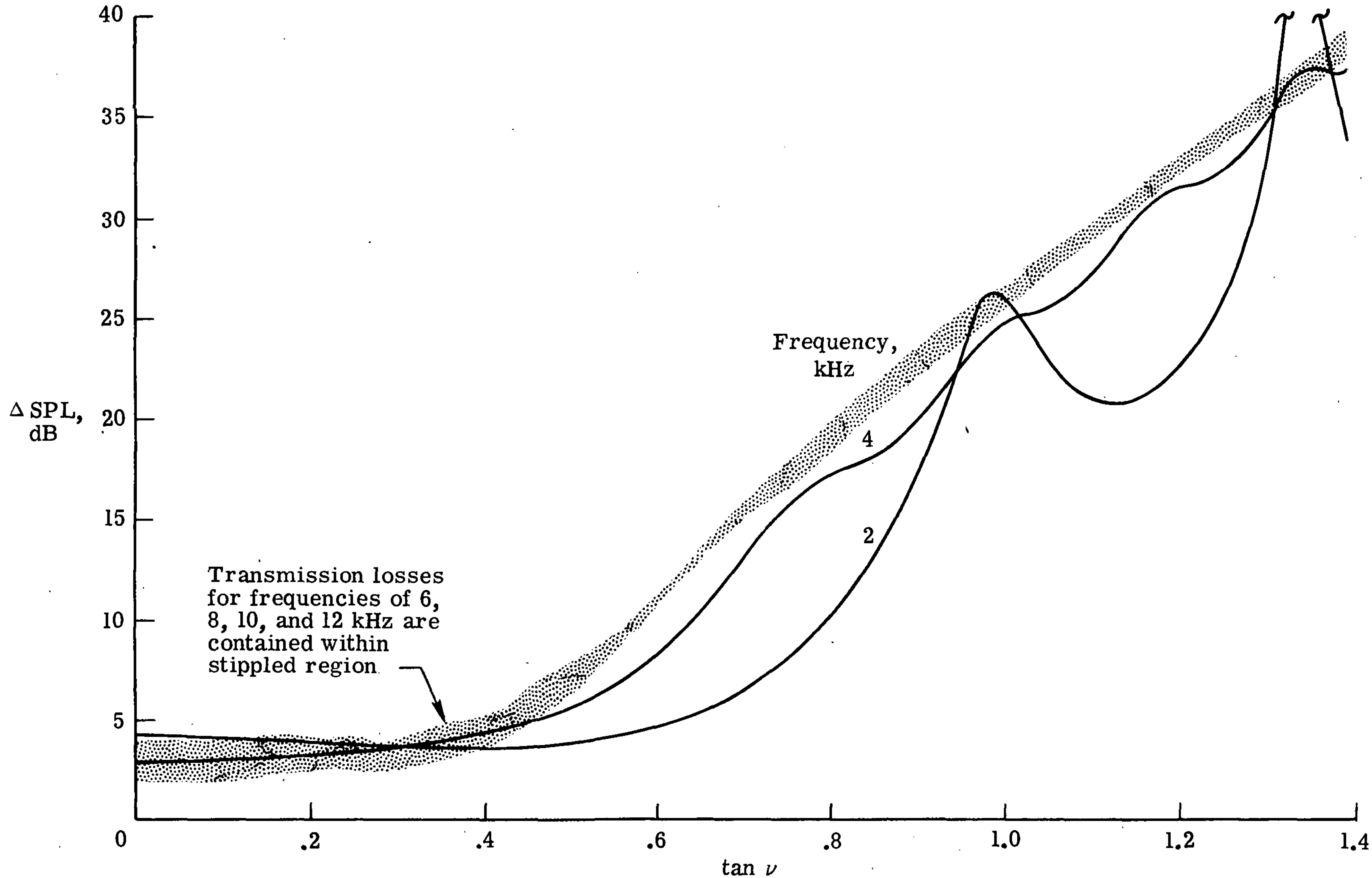

Figure 8.- Calculated spherical wave transmission loss through a helium layer.

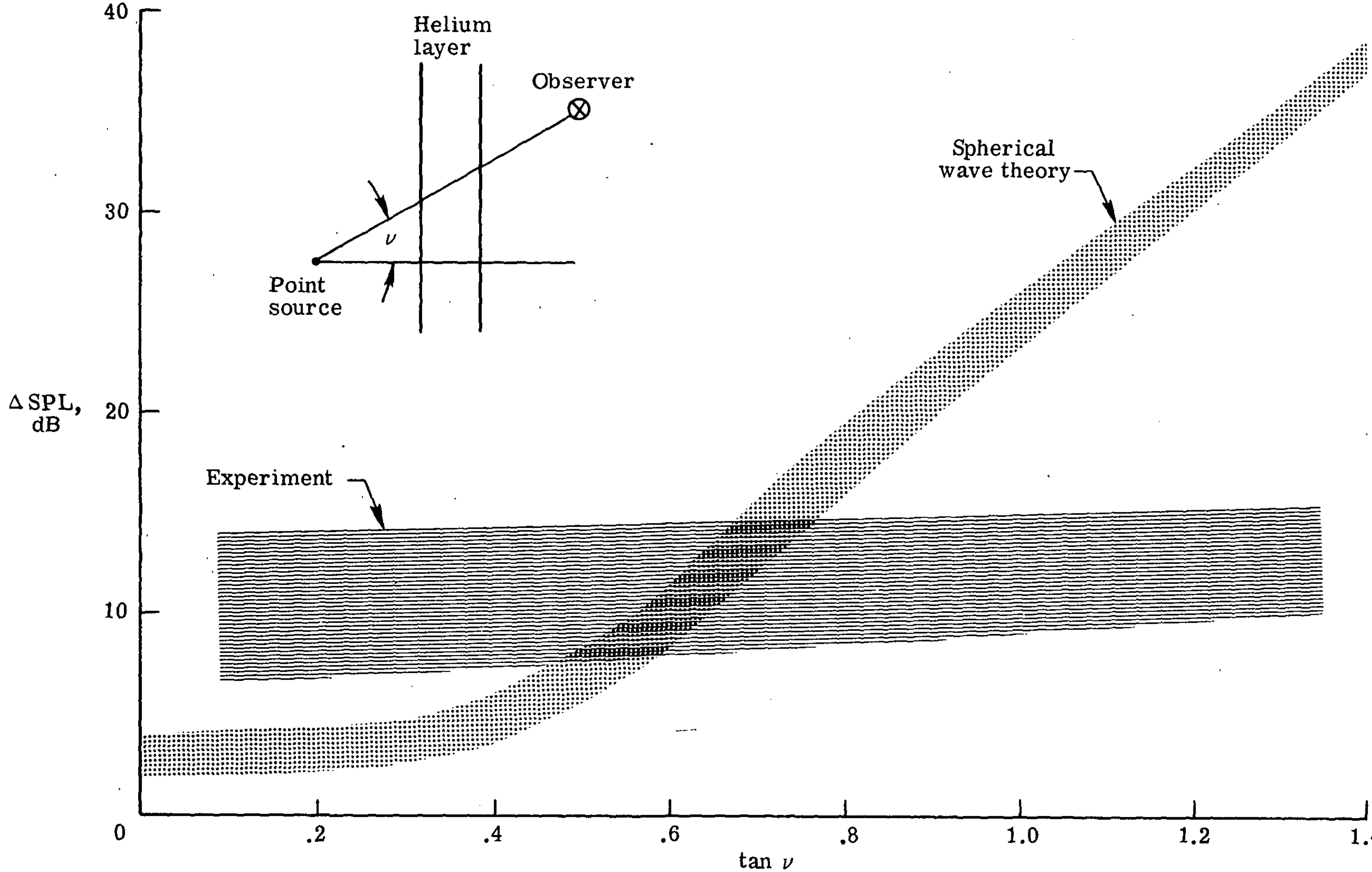

Figure 9.- Experimental and theoretical transmission losses through a 0.102-m-thick (4 in.) helium layer for frequencies from 4 to 12 kHz.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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