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# ATTENUATION OF SOUND AS A FUNCTION OF BARRIER ANGLE

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R. N. FOSS
APPLIED PHYSICS LABORATORY
UNIVERSITY OF WASHINGTON

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16. Abstract

Oblique wall noise barriers were investigated for angular dependence of attenuation. Experiments with a model at 5 kHz showed less than 1 dB difference from normal incidence to 45° incidence. Variations may approach 2 dB at angles near 70° from normal incidence. Thus, the obliqueness of the wall may be neglected for most practical problems.

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## SUMMARY

In most cases where a wall is shielding a noise source, the wall is not exactly perpendicular to a line connecting the source and the listener, but rather the sound crosses the barrier at an angle. The purpose of the experiments described here was to ascertain if there is an angular dependence to the sound shielding properties. The conclusions reached, as a result of these experiments, are that for angles less than 30° from normal incidence there is very little effect, and that for angles from 30° up to perhaps 70° the effect is small. The length of the experimental wall was too short to allow firm conclusions about the effects for still greater angles. However, it is probable that for an infinite wall with a true knife edge made of an acoustically nonconductive material, the angle would have little effect to very near 90°. In the majority of practical cases, the sound ray angle-of-crossing would be in the realm where these experiments show the angle effect to be small compared to other likely errors.

## EXPERIMENTAL SETUP

The experiment consisted of transmitting acoustic tone bursts approximately 1-msec long at 5.193 kHz and 10.019 kHz across an acoustic barrier to a receiving microphone. The source and microphone were carefully constructed to approximate point radiators as much as possible. The electronics, noise sources, microphones, height adjustment procedures, etc., were similar to those used for the single barrier noise measurements, which are fully described in APL-UW Report No. 7509, dated 30 June 1975. The chief difference was in the details of the test wall, which consisted of a 10-ft long x 4-ft high x 5/8-in. thick piece of plasterboard supported by an angle-iron structure. For the tests reported in APL-UW 7509, the wall was arranged such that it could be quickly and reproducibly raised and lowered. For these tests, the wall was altered so that, instead, it could be rotated horizontally about its center. To delay sound passing around the ends of the wall at higher angles, the wall was further modified by adding "wings" on each end, as shown in Figure 1. The noise source and microphone were placed on opposite sides of the wall in such a manner that a line directly connecting them would pass through the wall's axis of rotation. The experiment then consisted of noting the amplitude of the received pulses as the angle of the test wall was varied. For some tests, the plasterboard itself (1.5 cm wide) formed the upper edge of the wall; for other tests, a 1/8-in. (0.318-cm) thick piece of aluminum several inches wide was attached to the top to produce a thinner edge; for other tests, a 2 x 4 was bolted beside the plasterboard to produce a top edge 5 cm wide.

## EXPERIMENTAL PROCEDURE

Better details of the fine-structure observed in this particular experiment would be obtained using a slow-moving, continuous-drive motor to slowly rotate the wall, a selsyn type pick-off to drive the horizontal (angle) axis of the chart, and an appropriately gated receiver to plot the amplitude. However, since this degree of elaboration was not available, the experiment was performed by hand. The procedure involved setting the wall to a predetermined angle and then observing the amplitude of the received pulse on an oscilloscope; the wall was then indexed to a new angular position and the experiment repeated. The results of this process were then hand plotted.

It was not initially anticipated that much fine-structure would exist with this setup, and so much of the initial work was performed using 5° increments of the test wall. Only when these experiments were nearly completed was it clear that the amplitude changed so rapidly with angle that to get a true picture of the functional variation with angle would require the examination of increments considerable finer than 5°. Most of the graphs shown in this report were done using 1° steps; this was usually adequate to delineate the shape of the curve, although some sharper peaks required examination at 1/2° increments in order to ascertain their full magnitude.

As discussed in APL-UW Report 7509, there is some jitter in the received signal caused by air motion, so it was necessary to "eye integrate" a number of pulses to obtain a reasonable value for each point. This procedure considerably hampered and lengthened the data-taking process. However, the fine structure that is shown on many of the charts is probably real and not a function of this fluctuation, since these readings were frequently checked, cross-checked, and re-zeroed to normal incidence. The inverse is not necessarily true, i.e., it is entirely possible that there is some fine-structure that was missed; this would certainly be the case when the data were taken at increments coarser than 1°. The data for the 5/8-in. plasterboard wall with wings were carefully retaken at 1° increments and probably represent a good picture of the actual fine-structure existing in this experimental setup.

The experiment was conducted, as previously mentioned, with a 10-ft long wall section which was rotated about its center--thus the radius of rotation was only 5 ft. This is certainly far from an infinitely long wall, and raises the question of whether some spurious effects would be caused by the relative shortness of the wall segment--more specifically, whether sound diffracted around the ends of the wall would appreciably perturb the results.

If one makes the over-simplified assumption that the sound going around the ends arrives at the same time and precisely in phase with the signal diffracted over the top, this "side" signal could certainly be of sufficient magnitude to perturb the results. Based on this assumption, with the source and microphone at the same height as the top of the wall, a 1-dB variation could occur for angles in excess of 52° at 5 kHz, and for angles in excess of 68° at 10 kHz; with the source and the microphone 10 cm or more below the top of the wall, this 1-dB variation would occur at angles less than 20° from normal incidence at either frequency. This means that had the experiment been conducted with steady-state signals in an anechoic chamber (on a wall without wings), spurious peaks and valleys would have been found as the over-the-top and around-the-end signals went through enhancement and cancellation. The actual experiments, however, were carried out using tone burst techniques with the timing such that (particularly with the wings added) the around-the-end pulses were sufficiently delayed with respect to the pulse going over the top so that (for most angles) there would be no interference.

The 10-kHz pulses were slightly less than 1 msec long and the 5-kHz pulses somewhat over 1 msec. The particular part of the waveform that was normally examined when comparing the relative heights was in the center of the transmitted pulse so that, in general, the point of examination was clearly less than 1 msec from the start of the pulse. Thus, if the sound passing around the ends of the wall were delayed more than 1 msec relative to the direct signal, the measurement would not be perturbed by the end-of-the-wall signals. Calculation shows that end-of-wall pulses will be delayed vis-à-vis the measurement pulse by at least this amount for all angles less than about 70°. For the particular geometry used, as the angle progresses beyond 70°, it becomes increasingly more difficult to separate acoustic effects caused by end-around sound from acoustic effects caused by the wall angle or thickness.

The wall was therefore modified with wings to produce the Z-shaped plan view shown in Figure 1. The purpose of the wings was to delay transmission of sound around the ends by making the sound paths sufficiently long that the sound would not interfere with the main pulse at higher wall angles. The plots shown in this report were all taken using this Z-shaped wall.

## MEASUREMENT RESULTS

Some of the results of these tests are plotted in Figures 2 through 8. In each case, the plots shown were normalized to the signal that was received when the wall was at normal incidence; i.e., the attenuation was not measured absolutely but relatively, as a function of rotation angle. For the convenience of the reader, some curves show the actual (zero angle) attenuation of the wall as computed from the geometry and reference to Fresnel's curve.

As can be seen, the plots still go through fluctuations at angles beyond 70°. During those periods when peaks or valleys were found, the entire oscilloscope trace tended to increase or decrease--the received signal did not tend to be unduly distorted or tilted, as would be expected if an interfering pulse were slowly overlapping as the wall was turned. This indicates the peaks and valleys in the data are (except at very high angles) a function of the wall itself rather than end effects.

It is possible that some of these peaks and valleys are caused by the finite thickness of the wall (i.e., the fact that the top of the wall was not a knife edge). In that case, one could expect these peaks and valleys to occur where the "effective thickness" (in air) of the top of the wall was some multiple of a half wavelength. If it is further assumed that the effective thickness is represented by the total distance that a ray passing over the top would be touching the wall, it is obvious that the effective thickness increases as a function of angle. Table I shows those angles at which the effective thickness would be one-half wavelength or some multiple thereof for each of the two test frequencies. Some of the measurements show definite effects at these angles, others do not.

Figure 2 was taken at 5.193 kHz with the 1/8-in. aluminum strap on the top of the wall so that the ultimate wall top was about 0.318 cm thick. This particular case is closest to having a knife edge, although, particularly at the higher angles, other features of the wall no doubt come into play to some extent. As can be seen from Figure 2, if the microphone and source are above the wall, the attenuation increases slightly as the angle is increased until the wall angle becomes fairly high, whereas if the wall is higher than the microphone and source, the effect of wall rotation is to decrease the attenuation (i.e., there is actually somewhat more sound behind the wall than there would have been had the wall been at normal incidence). For angles smaller than 45°, the deviation from normal is less than 1 dB at all the measurement heights. For angles greater than 45°, the deviation from normal incidence depends more strongly on the relative wall height. When the wall was 10 cm below the source-microphone path, the deviation was less than 1 dB out to nearly 85°. When the wall was higher than the source and microphone by 10 and 20 cm, the attenuation increased rapidly as the angle approached 90°; this effect was probably caused by the wings attached to the wall. Although the wings make the experiment more reliable at large angles, as 90° is approached they act like a double or triple wall, which can produce attenuation considerably in excess of that caused by a single wall.

As can be seen by referring to Table I, the first angle at which the crossing path becomes a half wavelength is 84.5°; one wavelength is in excess of 87°, etc. These angles are sufficiently high that any effect due to the effective thickness of the top edge is swamped by other phenomena in the experimental situation.

Table I. Angle of Ray Crossing to Produce "Effective Thickness" of Even Numbers of Half Wavelengths for 5.193 kHz

| | Angle (deg) | | |
|---|---|---|---|
| | 5.04-cm thick wall $T_\lambda = 0.77$ * | 1.5-cm thick wall $T_\lambda = 0.23$ | 0.318-cm thick wall $T_\lambda = 0.048$ |
| 0.5 λ | - | 62.60 | 84.50 |
| 1.0 λ | 39.90 | 76.80 | 87.25 |
| 1.5 λ | 59.24 | 81.25 | 88.17 |
| 2.0 λ | 67.44 | 83.45 | 88.62 |
| 2.5 λ | 72.13 | 84.76 | 88.90 |
| 3.0 λ | 75.18 | 85.64 | 89.08 |
| 3.5 λ | 77.34 | 86.26 | - |
| 4.0 λ | 78.94 | 86.73 | - |

---

*$T_\lambda$ = wall thickness in wavelengths. For 5.193 kHz, λ = 6.57 cm.

Figure 3 shows the data taken with the top of the plasterboard itself as the upper edge. This was about 1.5 cm wide, or, at 5.193 kHz, slightly less than one-quarter wavelength. Examination of Figure 3 shows that the maximum deviation is less than 0.2 dB up to nearly 40°, less than 1 dB up to 50°, and less than 1.5 dB up to nearly 75°. Once again, the configurations where the wall is higher than the source and microphone tend to show rapidly increasing attenuation as the 90° point is reached; again, this is probably due to the multiple-wall effect caused by the addition of the wings. Figure 3 indicates the angles that would create multiples of one-half wavelength. As can be seen, some of the consistent "wiggles" on the curve do occur at these particular angles; however, there are many other wiggles that occur at other positions, and involve phenomena more complex than the simple thickness of the upper edge.

Figure 4 is a similar plot of the 5-kHz data for the various effective wall heights, except this time a 2 x 4 has been bolted parallel with the top of the wall to bring the total thickness of the top edge to 5.04 cm. This is approximately three-fourths wavelength at 5.193 kHz. Again, the deviation is not very great until the higher angles are reached. The graph also shows the positions where the ray path across the top of the wall would be some multiple of one-half wavelength; the one-half wavelength position, of course, does not appear since the wall is already more than one-half wavelength thick. Once again, nothing unique takes place at these particular angles; again the deviation from normal is very small below 45°, and is less than 1 dB to nearly 60°.

Figures 5 through 8 are multiple plots with the wall height held fixed and the relative attenuation versus angle plotted for each of the three wall top thicknesses. All of these data are for 5.193 kHz. They are plotted together even though the situations are not completely comparable, since for the 1.5-cm and 5.04-cm cases the wings were exactly as high as the wall top, while for the 0.138-cm case the top was raised by the aluminum knife edge, leaving the wings a couple of inches shorter than the wall top. The effect can be seen in Figure 6, where the edge that is 0.318 cm thick shows a trend toward less attenuation at the 90° point, while the thicker edges show the reverse. For cases where the wings are higher than the source and microphone, the high-angle tendencies are the same for all thicknesses. Obviously the thickness of the wall top does have some effect on how the wall acts acoustically; however, its effect is relatively small for the range of thicknesses examined.

The experiment was performed at a little over 5 kHz. The "effective frequency" of the noise from automobiles, on the other hand, is nearer 500 Hz. On this scale, the data are equivalent to cars about 56 ft from the wall, and a listener about 61 ft behind the wall. Where the experiment was performed with the wall 10 cm lower than the source and microphone, the full-scale equivalent would be a wall 3-1/3 ft lower than the source and listener. The case where they are all the same height would, of course, still be the same. The -10 cm case would correspond to a wall about 3-1/3 ft higher than the listener's ear, and the -20 cm case would correspond to a wall about 6-2/3 ft higher. These geometries represent situations that are of real interest for highway noise suppression.

## CONCLUSIONS

For angles less than 45° from normal incidence, the effect of attenuation vs angle is small, and can certainly be neglected for virtually all meaningful calculations. In the region from 45° to 75°, the effect of angle depends on a number of variables and may be of some small significance in some cases; however, for most situations, it can be reasonably neglected. When the wall is not very high (i.e., the attenuation of the wall is small), the angle of crossing has little effect. When the wall is relatively high (i.e., the attenuation is rather high even at normal incidence), the functional relationship between attenuation and the angle of crossing is slightly more significant; however, it is likely that even in this case other errors in the attenuation determination would be more significant than the effect of this angular dependence.

The experimental setup was such that no firm conclusions could be drawn for angles above 75°. However, in general, at very high angles the attenuation tends to be less than at normal incidence; i.e., the wall tends to be somewhat less effective as a noise barrier. On the other hand, it is probably not likely that there would be, in practice, many cases where a perfectly straight wall would run for a sufficient distance to include angles in excess of ±70°.

The data show numerous peaks and valleys at the higher angles. However, since the problem of concern is vehicle noise, which has a rather broad spectrum, there would be at least some tendency for the peaks at one frequency to be compensated for by a valley at a different frequency; thus, some of the peaks and valleys in the fine-sturcture seen in these plots would probably tend to smooth out. Since almost all the walls or barriers encountered in actual practice have total excursions subtending less than ±70° (and, indeed, in many cases the wall is stopped by the presence of hills, buildings, etc., at angles less than ±45°), it seems reasonable for routine calculations to ignore the effect of the angle at which sound crosses the wall or barrier. It should be kept in mind, however, that this is a simplifying approximation and there conceivably could be some cases where the angle crossing effect should be considered.

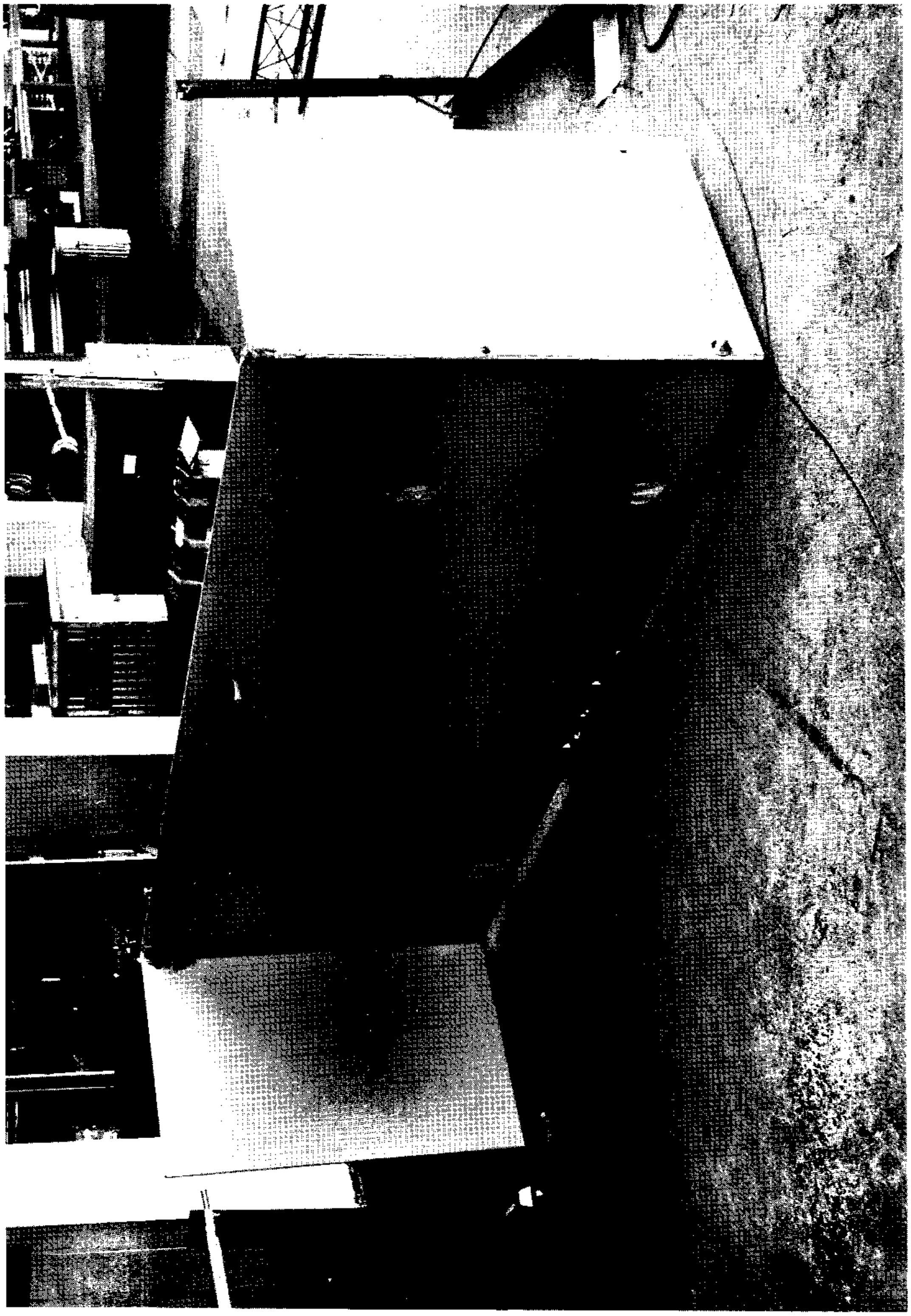

Figure 1

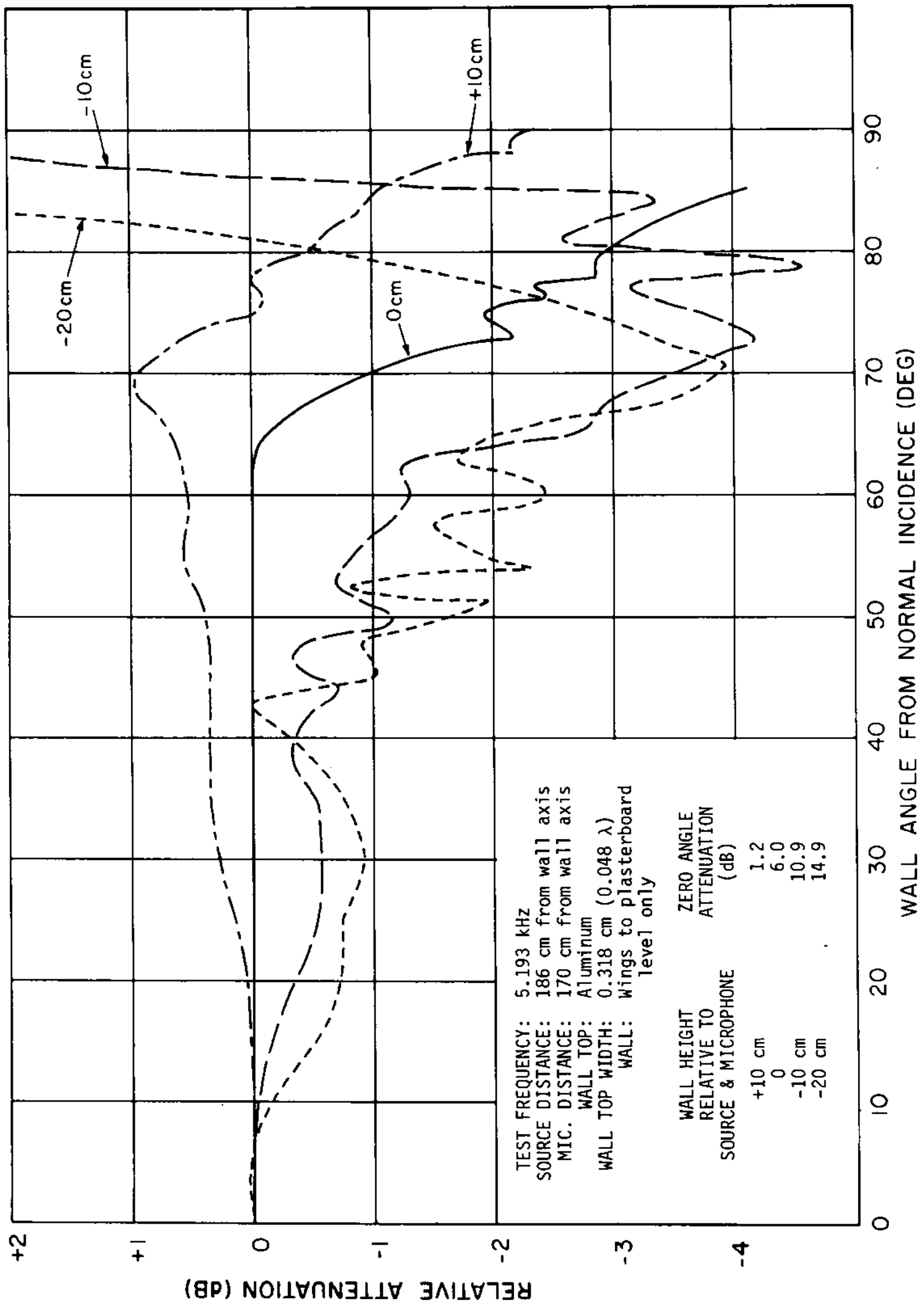
-10cm
+10cm
-20cm
0cm
TEST FREQUENCY: 5.193 kHz
SOURCE DISTANCE: 186 cm from wall axis
MIC. DISTANCE: 170 cm from wall axis
WALL TOP: Aluminum
WALL TOP WIDTH: 0.318 cm (0.048 λ)
WALL: Wings to plasterboard level only
WALL HEIGHT RELATIVE TO SOURCE & MICROPHONE
ZERO ANGLE ATTENUATION (dB)
+10 cm 1.2
0 6.0
-10 cm 10.9
-20 cm 14.9
0
10
20
30
40
50
60
70
80
90
WALL ANGLE FROM NORMAL INCIDENCE (DEG)
+2
+1
0
-1
-2
-3
-4
RELATIVE ATTENUATION (dB)

Figure 2

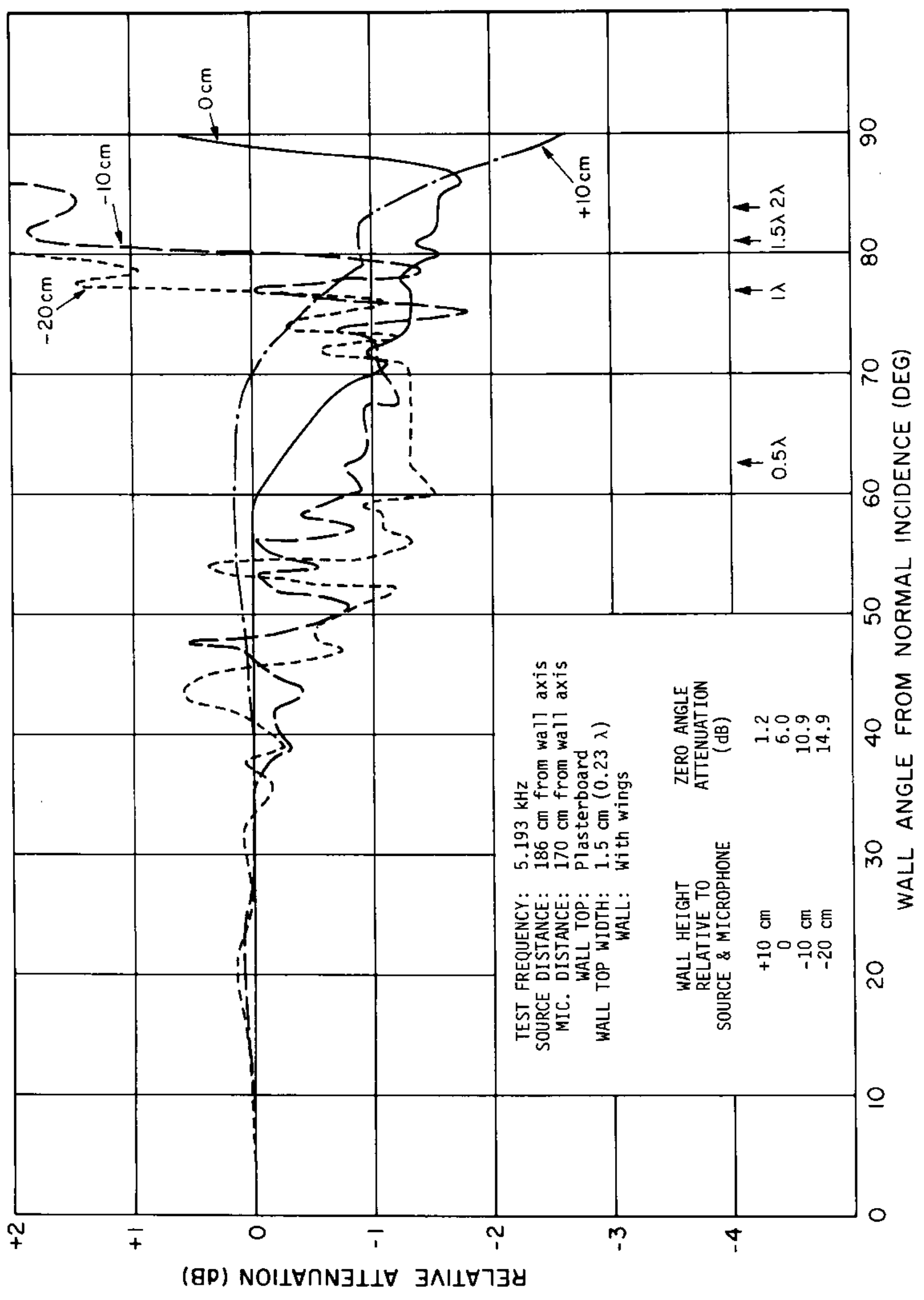
TEST FREQUENCY: 5.193 kHz
SOURCE DISTANCE: 186 cm from wall axis
MIC. DISTANCE: 170 cm from wall axis
WALL TOP: Plasterboard
WALL TOP WIDTH: 1.5 cm (0.23 λ)
WALL: With wings
WALL HEIGHT RELATIVE TO SOURCE & MICROPHONE
ZERO ANGLE ATTENUATION (dB)
+10 cm 1.2
0 6.0
-10 cm 10.9
-20 cm 14.9
0 cm
-10 cm
-20 cm
+10 cm
0.5λ
1λ
1.5λ
2λ
+2
+1
0
-1
-2
-3
-4
RELATIVE ATTENUATION (dB)
0
10
20
30
40
50
60
70
80
90
WALL ANGLE FROM NORMAL INCIDENCE (DEG)

Figure 3

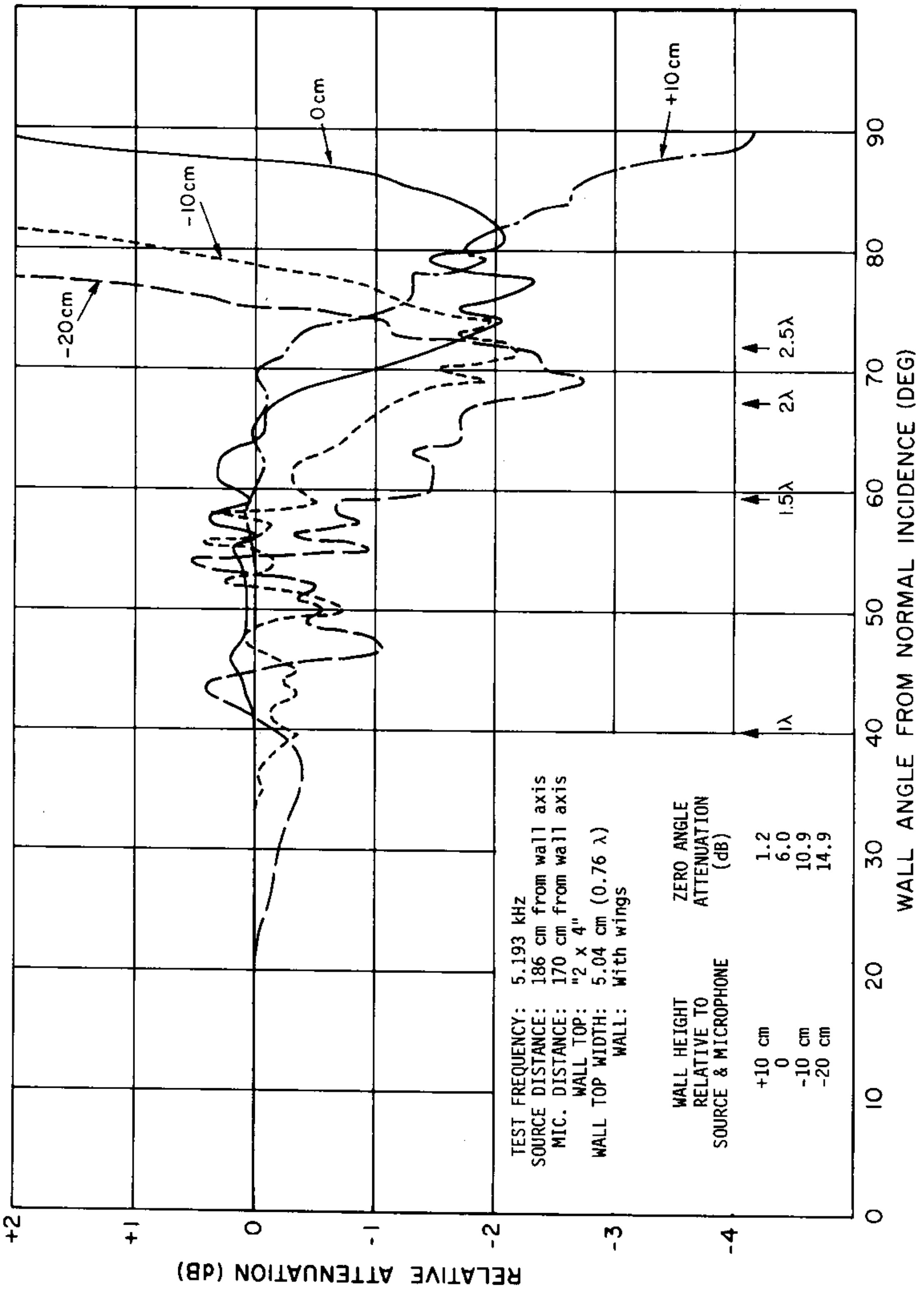
RELATIVE ATTENUATION (dB)
+2
+1
0
-1
-2
-3
-4
WALL ANGLE FROM NORMAL INCIDENCE (DEG)
0
10
20
30
40
50
60
70
80
90
+10cm
0cm
-10cm
-20cm
λ
1.5λ
2λ
2.5λ
TEST FREQUENCY: 5.193 kHz
SOURCE DISTANCE: 186 cm from wall axis
MIC. DISTANCE: 170 cm from wall axis
WALL TOP: "2 x 4"
WALL TOP WIDTH: 5.04 cm (0.76 λ)
WALL: With wings
WALL HEIGHT RELATIVE TO SOURCE & MICROPHONE
ZERO ANGLE ATTENUATION (dB)
+10 cm 1.2
0 6.0
-10 cm 10.9
-20 cm 14.9

Figure 4

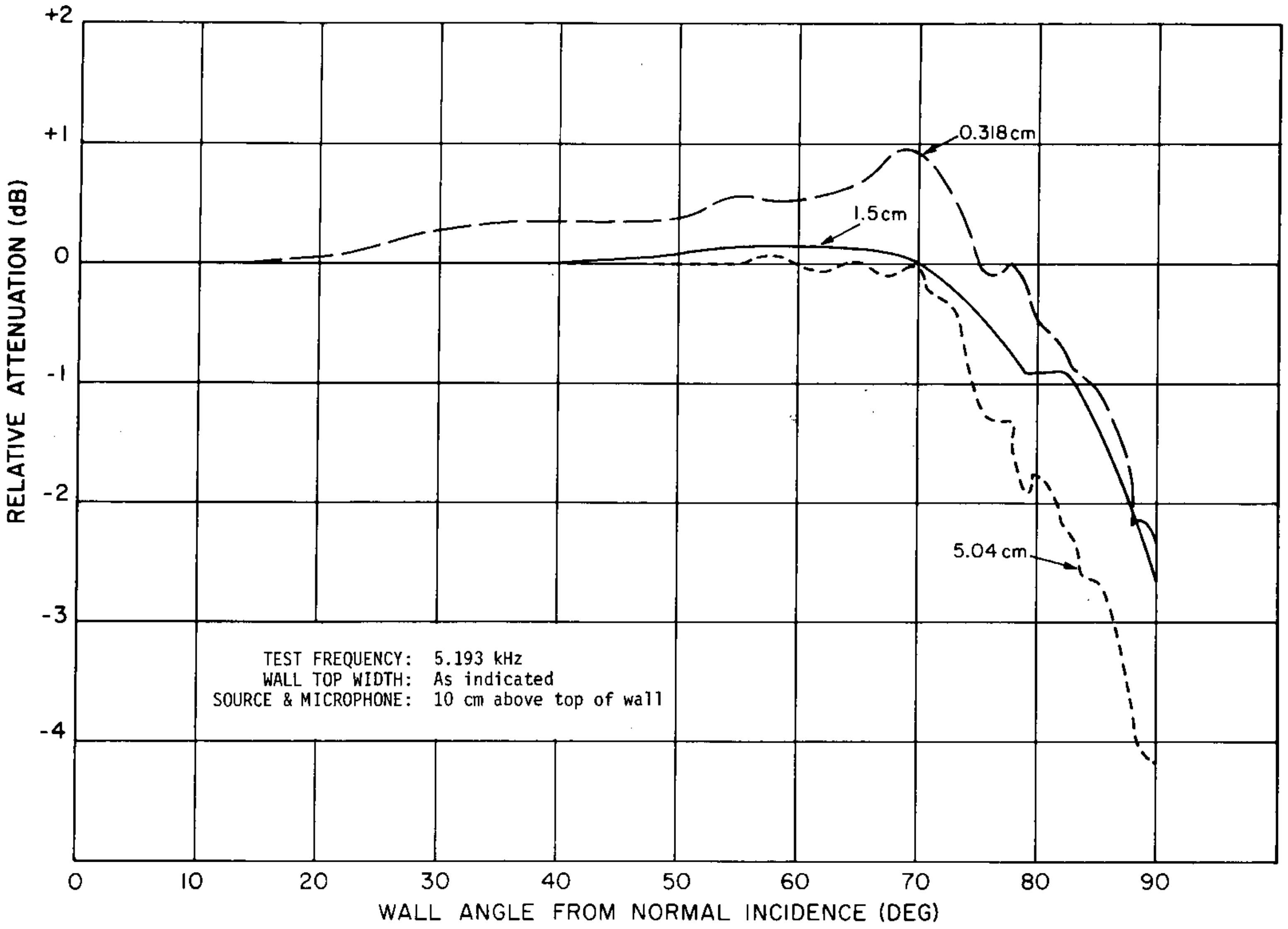
+2
+1
0
-1
-2
-3
-4
RELATIVE ATTENUATION (dB)
0
10
20
30
40
50
60
70
80
90
WALL ANGLE FROM NORMAL INCIDENCE (DEG)
0.318cm
1.5cm
5.04cm
TEST FREQUENCY: 5.193 kHz
WALL TOP WIDTH: As indicated
SOURCE & MICROPHONE: 10 cm above top of wall

Figure 5

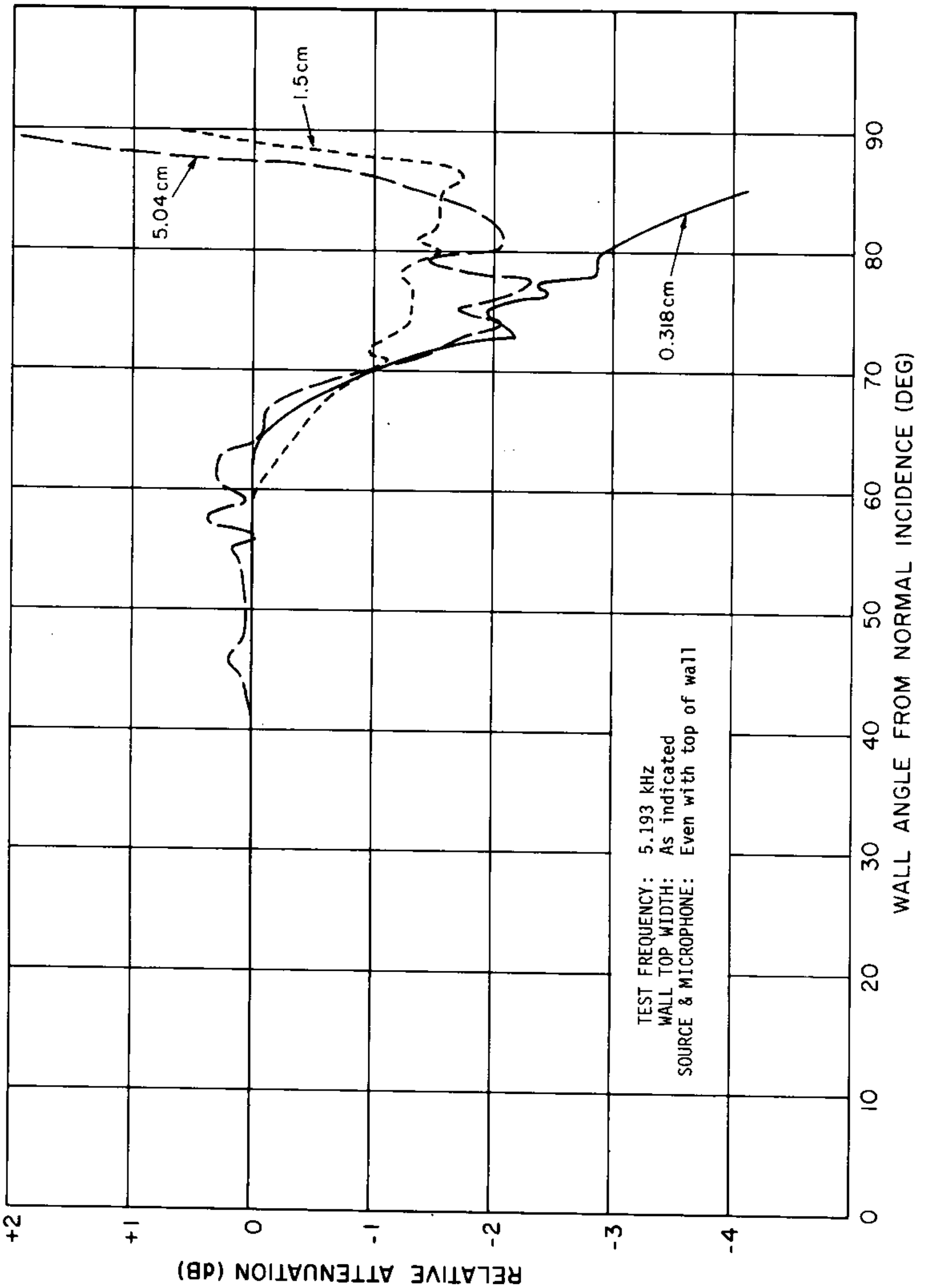
1.5 cm
5.04 cm
0.318 cm
TEST FREQUENCY: 5.193 kHz
WALL TOP WIDTH: As indicated
SOURCE & MICROPHONE: Even with top of wall
0
10
20
30
40
50
60
70
80
90
WALL ANGLE FROM NORMAL INCIDENCE (DEG)
+2
+1
0
-1
-2
-3
-4
RELATIVE ATTENUATION (dB)

Figure 6

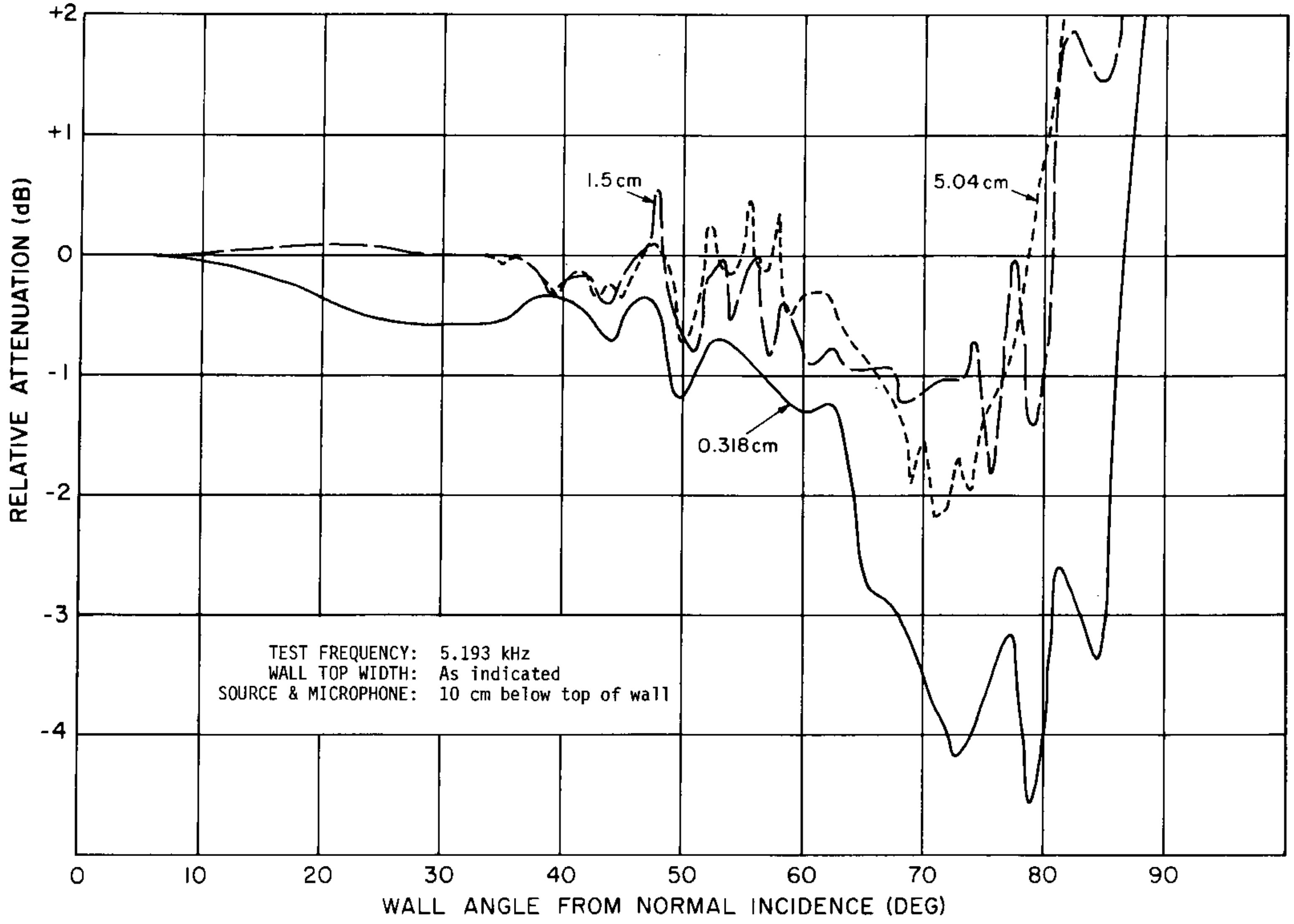
+2
+1
0
-1
-2
-3
-4
RELATIVE ATTENUATION (dB)
0
10
20
30
40
50
60
70
80
90
WALL ANGLE FROM NORMAL INCIDENCE (DEG)
1.5 cm
5.04 cm
0.318 cm
TEST FREQUENCY: 5.193 kHz
WALL TOP WIDTH: As indicated
SOURCE & MICROPHONE: 10 cm below top of wall

Figure 7

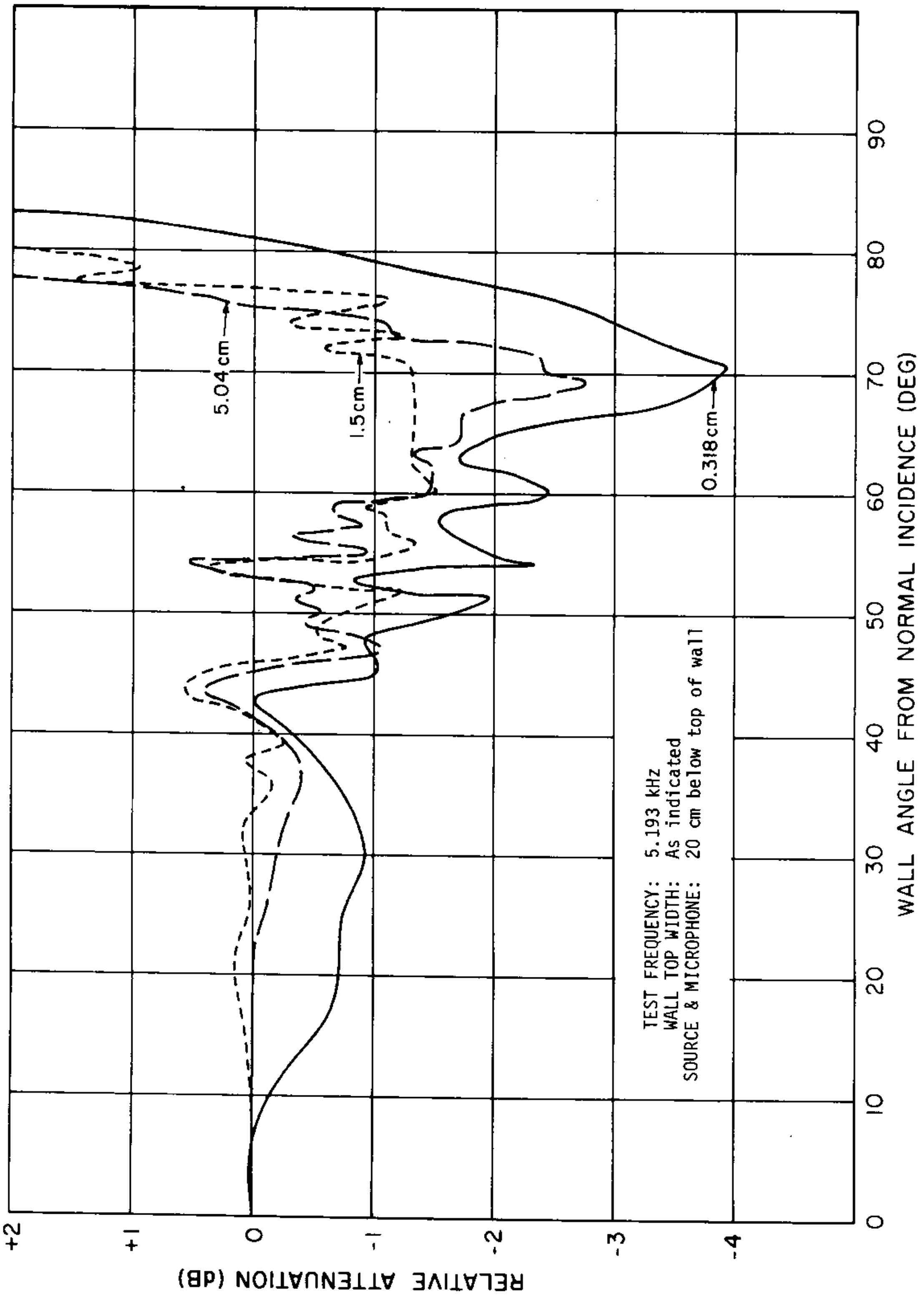
TEST FREQUENCY: 5.193 kHz
WALL TOP WIDTH: As indicated
SOURCE & MICROPHONE: 20 cm below top of wall
5.04 cm
1.5 cm
0.318 cm
WALL ANGLE FROM NORMAL INCIDENCE (DEG)
0
10
20
30
40
50
60
70
80
90
RELATIVE ATTENUATION (dB)
+2
+1
0
-1
-2
-3
-4

Figure 8

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