Environmental Effects on the Speed of Sound*

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A detailed analysis of the environmental effects of temperature and humidity on the speed of sound is presented. An overview of the available literature reveals serious shortcomings for practical applications. New graphs, tables, and equations present the findings in a more useful manner for sound reinforcement “se. The results show that tight control of temperature and humidity must accompany the popular trend of splitting microseconds when time correcting sound systems. Failure to do so makes precise time correction a” exercise in futility.

0 INTRODUCTION

This paper presents, expands, and clarifies the environmental effects of temperature and humidity on the speed of sound. These effects increase the speed of sound and complicate the task of room equalization immensely—much more so than previously thought.

The dramatic effect of relative humidity on sound absorption appears as a separate section and helps explain many mysteries involving startling changes in room response from day to day. Even a modest change in relative humidity of only 10% can cause an additional 35 dB per 1000 ft (300 m) of absorption.

In one sense, nothing new appears in this paper. The major effects described and the equations presented all exist within published books on acoustics. Some from the *Journal of the Acoustical Society of America* are 45 years old. However, this does not reduce the importance of this paper. It is assumed that members of the Acoustical Society of America are familiar with this material. Unfortunately, very few people equalizing rooms for permanent sound systems belong to that society. This paper is for the members of the Audio Engineering Society who are in the trenches every day and need all the assistance they can get.

What *is* new is the table and graphic treatment of the material. Everything known regarding the effects of temperature and humidity on the speed of sound appears in this new form, as does the material on sound absorption. Experience shows tabulated and graphed data to he more useful than equations. Practical applications require concise look-up facts.

Before presenting the detailed analyses, a question should be answered: why bother?

This is not a facetious question. Many people realize that sound velocity depends upon temperature, barometric pressure, relative humidity, altitude, air composition, and so on. Only somewhere they learned that they may ignore these effects, that they are not significant. Well, 30 years ago the author may have agreed with you. Then we were just beginning to understand what room response meant, much less were we able to do anything about it. We then developed ways to view and alter room responses. Graphic equalizers and real-time analyzers opened up a whole new window of opportunity for improving playback audio.

Progress continued slowly until Richard Heyser gave us time-delay spectrometry (TDS). Then we experienced one of those step function jumps in our ability to view our acoustic environment. For the first time we could actually see what we had been dealing with all along.

Today we have a whole new army attacking room problems with a vengeance. Racks of equalizers and delay units arm these combatants as they wage war on all those response peaks and valleys. Each year they demand finer equalization tools and smaller delay increments with which to continue the fight. All this is fine. Only we must not forget mother nature. TDS-based test equipment allows us to see far more than is probably good for us. And there is a natural tendency to fix something if we can see it-without regard to relevancy.

The thesis of this paper is that tight control of temperature and relative humidity *must* accompany the use of very small time-delay increments to fix room response

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problems. Perhaps an example best illustrates the importance of tightly controlling the environment of sound systems.

0.1 An Example

For this example I will jump ahead and use data from the various graphs and tables presented. I hope this approach will encourage you to wade through the forthcoming material. As detailed as it must be, it is not terribly interesting. However, the results are.

This simple example does not even require diagrams. Consider a listening spot located such that the direct sound must travel 50 ft (15 m) to the listener. This same spot receives one reflected arrival that travels 140 ft (42 m), say 70 ft (21 m) to a sidewall and another 70 ft (21 m) back to the listener's ear. Ignore all other delayed arrivals. The reflected wave arrives with some sort of phase relationship to the direct wave. This relationship is a function of the distance traveled, the frequency involved, and the speed of sound.

Assume the room temperature was 20°C with 30% relative humidity when measurements where taken. Table 3 shows that the velocity of sound is 3.71% faster than standard velocity (1087.42 ft/s). Using a test tone of 10 kHz, calculate the following information:

Velocity of sound $1087.42 \times 1.0371 = 1127.763$ ft/s

Wavelength $\frac{1127.763}{10 \text{ kHz}} = 0.1127763$ ft

Number of cycles traveled for 50 ft $\frac{50}{0.1127763} = 443.36$

Number of cycles traveled for 140 ft $\frac{140}{0.1127763} = 1241.40$

For purposes of this example, the only thing of interest is the decimal fractions of a cycle. For all practical purposes the two waves are in phase (0.36 cycle verses 0.40 cycle), that is, the delayed and attenuated reflected wave arrives essentially in phase. So the two waves will add. A little equalization easily corrects this bump and the sound contractor is happy.

Until the environment changes. Assume the temperature rises to 30°C with 80% relative humidity. Consulting Table 3 shows that the velocity of sound now is 5.9% faster than standard. The casual observer mistakenly figures it is only a difference of 2.19%, so there is no problem. The casual observer is wrong.

Recalculation gives the following:

Velocity of sound $1087.42 \times 1.059 = 1151.578$ ft/s

Wavelength $\frac{1151.578}{10 \text{ kHz}} = 0.1151578$ ft

Number of cycles traveled for 50 ft $\frac{50}{0.1151578} = 434.19$

Number of cycles traveled for 140 ft $\frac{140}{0.1151578} = 1215.72$

Okay, the velocity of sound increased. This creates a longer wavelength. So traveling the same distances takes fewer cycles. Nothing too interesting yet. However, careful examination of the two decimal fractions of a cycle reveals that they are essentially *out of phase.* The difference between them is 0.53 cycle, or about 180°. Even to the casual observer this is not good. The applied equalization is now in the wrong direction.

This example illustrates the fallacy of thinking that you can ignore velocity changes since they affect direct and reflected waves equally. This simply is not true.

Complicating things further is the change in absorption due to the change in relative humidity. Table 6 and Fig. 6 show a drop of 39 dB per 1000 ft (300 m) due to the increased relative humidity (ignoring the temperature effects of 30°C). Since the example involves a distance of 140 ft, there is 5.46 dB less absorption. So not only does the signal arrive out of phase, but it is also about 5.5 dB bigger.

The point of all this is that even a small percentage change in the speed of sound can have disastrous effects on a sound system. Often overlooked is that *the small percentage change is for every cycle undergone by the wave.* It is a trap to think of the change as only a few percent and dismiss it. Think of the hundreds and thousands of cycles existing within any sound room. Each one has its wavelength altered by this percentage. If a 1% change affects hundreds of cycles, it alters the acoustics of the whole system. No wonder that all those hours spent equalizing are sometimes in vain.

0.2 Overview

Sec. 1 presents historical background information to put into perspective the number of years spent in investigating sound, its velocity, and the environmental factors affecting it. Temperature and humidity effects appear as Sec. 2. Following this, Sec. 3 outlines the effect of relative humidity on sound absorption, and finally, Sec. 4 gives a brief summary of the paper.

Much work lies ahead in understanding how to control environmental effects so that room equalization, once done, will remain satisfactory for prolonged periods. I hope this paper succeeds in outlining the necessary areas of study and in stimulating others to probe further.

1 HISTORICAL BACKGROUND [1]

Investigation into the nature of sound dates back to earliest recorded history. Indeed, ancient writings show that Aristotle (384-322 B.C.) observed two things regarding sound: first that the propagation of sound involved the motion of the air, and second that high notes travel faster than low notes. (Batting 0.500 is not too bad for the ancient leagues.)

Since in the transmission of sound air does not appear to move, it is not surprising that other philosophers later denied Aristotle's view. Denials continued until 1660 when Robert Boyle in England definitely concluded that air is one medium for acoustic transmission

The next question was, how fast does sound travel? As early as 1635, Pierre Gassendi, while in Paris, made measurements of the velocity of sound in air. His value was 1473 Paris feet per second. (The Paris foot is approximately equivalent to 324.8 mm.) Later Marin Mersenne (1588 - 1648). a French natural philosopher often referred to as the "father of acoustics," corrected this to 1380 Paris feet per second, or about 450 m/s. Gassendi also demonstrated conclusively that velocity is independent of frequency, thus forever discrediting Aristotle's view.

In 1656 the Italian Borelli and his colleague Viviani made a very careful measurement and obtained 1077 Paris feet per second, or 350 m/s. It is clear that all these values suffer from a lack of reference to the temperature, humidity, and wind velocity conditions.

It was not until 1740 that the Italian Branconi showed definitely that the velocity of sound in air increases with temperature. This was two years after the French gave us our first good velocity figure.

The first measurement judged precise in the modern sense occurred under the direction of the Academy of Sciences of Paris in 1738, where cannon fire was used. When reduced to 0°C. the result was 332 m/s-a rather remarkable feat considering that careful repetitions during the rest of the eighteenth century and the first half of the nineteenth century gave results differing from this value by only a few meters per second. And 200 years later the best modern value [2] recorded was 331.45 ± 0.05 m/s in still, dry air under standard conditions of temperature and pressure (0°C and 760 mm of Hg pressure)--a scant 0.5-m/s difference from the French value.

Laplace was the first to show why temperature was important. He suggested that in all prior calculations errors occurred due to the assumption that the elastic motions of the air particles take place at constant temperature (isothermal law). In view of the rapidity of the motions, he reasoned that the gas molecules experience a small change in temperature. In 1816 he demonstrated that the compressions and rarefactions did not follow the isothermal law, but instead follow the adiabatic law in which the changes in temperature lead to a higher value of the elasticity. (Adiabatic refers to change in which there is no gain or loss of heat.)

Elasticity is the product of the pressure and the ratio of the two specific heats of the air. The ratio of the specific heats is symbolized by the lowercase Greek letter gamma. Laplace originally used results by LaRoche and Berard giving ??= 1.50. His results were off from the measured velocity, but not enough to discourage the theory. Later in his chapter on the velocity of sound in his *Mécanique Céleste* in 1825 he used the accurately measured value of ??= 1.35 by Clement and Desormes (1819). The revised calculations agreed very closely with experimental results. Some years later the revised value of ??= 1.40 led to complete agreement with the measured velocity.

The Laplace theory is so well established that it is now common practice to work backward to determine ??for various gases by precise measurements of the velocity of sound in the medium.

2 TEMPERATURE AND HUMIDITY EFFECTS ON THE SPEED OF SOUND

2.1 Introduction

This section presents the equations governing the temperature and humidity dependence of the speed of sound. All data are based on results published in the *CRC Handbook of Chemistry and Physics* [3] and in Hardy, Telefair, and Pielemeier's definitive paper [2].

2.2 General Equations

The theoretical expression for the speed of sound c in an ideal gas is

$$c = \sqrt{\frac{\gamma P}{p}} \quad (1)$$

where P is the ambient pressure, p the gas density, and ??the ratio of the specific heat of gas at constant pressure to that at constant volume.

The term ??is dependent upon the number of degrees of freedom of the gaseous molecule. The number of degrees of freedom depends upon the complexity of the molecule,

??= 1.67 for monatomic molecules
??= 1.40 for diatomic molecules
??= 1.33 for triatomic molecules.

Since air is composed primarily of diatomic molecules, the speed of sound in air is

$$c = \sqrt{\frac{1.4P}{p}} \quad (2)$$

The velocity of sound c in dry air has the following experimentally verified values:

$$c = 331.45 \pm 0.05 \text{ m/s} \quad (3)$$

or

$$c = 1087.42 \pm 0.16 \text{ ft/s} \quad (4)$$

for audio frequencies, at 0°C and 1 atm (760 mm Hg) with 0.03 mol-% of carbon dioxide.

2.3 Temperature Dependence

Substituting the equation of state of air of an ideal gas *(PV = RT)* and the definition of density p (mass per unit volume), Eq. (2) may be written as

$$c = \sqrt{\frac{1.4RT}{M}} \quad (5)$$

where R is the universal gas constant, T the absolute temperature, and M the mean molecular weight of the gas at sea level.

Eq. (5) reveals the temperature dependence and pressure independence of the speed of sound. An increase in pressure results in an equal increase in density.

Therefore there is no change in velocity due to a change in pressure. But this is true only if the temperature remains constant. Temperature changes cause density changes which do not affect pressure. Thus density is not a two-way street. Changes in pressure affect density but not vice versa. Humidity also affects density, causing changes in the velocity of sound. These effects are discussed in the next section.

Since *R* and *M* are constants, the speed of sound may be shown to have a first-order dependence on temperature as follows:

$$C_0 \sqrt{\frac{T}{273}} \tag{6}$$

where *T* is the temperature in kelvins and C_0 equals the reference speed of sound under defined conditions.

The speed of sound is seen to increase as the square root of the absolute temperature. Substituting centigrade conversion factors and the reference speed of sound gives

$$c := 331.45 \sqrt{1 + \frac{t}{273}} \tag{7}$$

or

$$c := 1087.42 \sqrt{1 + \frac{t}{273}} \tag{8}$$

where *t* is the temperature in degrees Celsius.

Graphs of Eqs. (7) and (8) are shown in Figs. 1 and 2, respectively. Table 1 tabulates results for Eqs. (7) and (8). A more useful presentation of these data is shown in Fig. 3, which graphs the percentage increase in the speed of sound due to temperature.

2.4 Humidity Dependence

All previous discussion assumed dry air. Attention turns now to the effects of moisture on the speed of sound. Moisture affects the density of air and hence, from Eq. (1). the speed of sound in air. Moist air is less dense than dry air (not particularly obvious), sop in Eq. (1) gets smaller. This causes an increase in the speed of sound. Moisture also causes the specific-heat ratio to decrease, which would cause the speed of sound to decrease. However, the decrease in density dominates, so the speed of sound increases with increasing moisture.

The literature is painfully lacking in practical specific treatments on the correlation between relative humidity and sound speed. Hardy et al. warn of the many inexact expressions existing in the textbooks, handbooks, and tables for the change in sound speed due to moisture. A rigorous analysis does exist in Pierce [4] and is used to develop a useful and accurate graph and table directly relating relative humidity to the percentage increase in the speed of sound.

Eq. (5) is exact for dry air. Two terms must be modified to include accurately the effects of moisture (water vapor) on the speed of sound. These are the specific-heat ratio (1.4 for dry air) and *M*, the average molecular weight of the different types of molecules in the air. Development of each of these terms follows. The terms *R* (universal gas constant) and *T* (absolute temperature) remain unchanged.

The specific-heat ratio ??can be expressed as an exact fraction by letting *d* equal the number of excited degrees of freedom for the air molecules. This gives

$$\gamma := \frac{d + 2}{d} \tag{9}$$

Since the composition of dry air is mostly two atom molecules, it is said to be a diatomic gas. Diatomic gases have 5 degrees of freedom, three translational and two rotational; thus *d* = 5 and ??= %, or 1.40, for dry air.

If *h* is defined to he equal to the fraction of molecules that are water, then the presence of water (with 6 degrees of freedom) causes the average number of degrees of freedom per molecule to increase to 5 + *h*. Eq. (9) can now be rewritten to include the effects of moisture for air **as**

$$\gamma_w := \frac{7 + h}{5 + h} \tag{10}$$

[It is noted that Eq. (10) is an alternative but equivalent

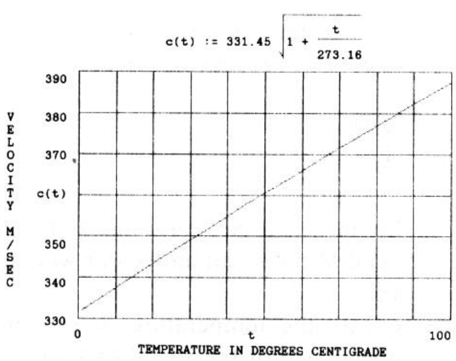

Fig. 1. Speed of Sound in m/s versus temperature.

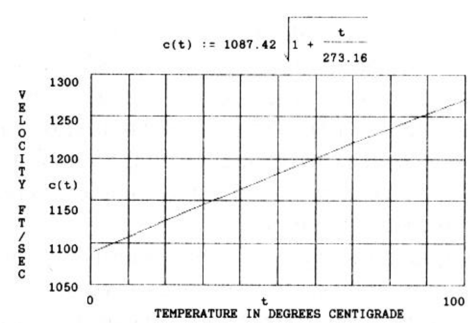

Fig. 2. Speed of sound in ft/s versus temperature.

expression to Humphreys's equation as used in thermodynamics.]

The average molecular weight of air decreases with added moisture. To see this, M is calculated first for dry air. Dry air composition is

78% nitrogen	(molecular weight = 28)
21% oxygen	(molecular weight = 32)
1% argon	(molecular weight = 40)

for a total molecular weight equal to

$$M = (0.78)(28) + (0.21)(32) + (0.01)(40) = 29$$

The presence of water (with a molecular weight of 18) causes the total average molecular weight to decrease to 29 − (29 − 18) h, or

$$M_w := 29 - 11\,h \tag{11}$$

Eqs. (10) and (11) modify the two terms from Eq. (5) affected by the addition of water vapor to air. Both are a function of the introduced water molecule fraction h. Relative humidity RH (expressed as a percentage) is defined such that

$$h := \frac{0.01\mathrm{RH}\ e(t)}{p} \tag{12}$$

where p equals ambient pressure (1.013×10^5 Pa for 1 atm reference pressure) and $e(t)$ is the vapor pressure of water at temperature t. For temperature values in degrees Celsius, representative values of $e(t)$ are

$e(5) = 872$ Pa	$e(20) = 2338$ Pa
$e(10) = 1228$ Pa	$e(30) = 4243$ Pa
$e(15) = 1705$ Pa	$e(40) = 7376$ Pa

To express the percentage increase in the speed of sound due to relative humidity all that remains is to take the ratio of the wet and dry speeds, subtract 1, and multiply by 100. Since both wet and dry speed terms involve the same constant terms $(R$ and $T)$, their ratio will cause these to cancel, leaving

$$\frac{c_w}{c_d} := \frac{\sqrt{\gamma_w/M_w}}{\sqrt{\gamma_d/M_d}} = \frac{\sqrt{\gamma_w/M_w}}{\sqrt{1.4/29}} = 4.5513\sqrt{\frac{\gamma_w}{M_w}}\ . \tag{13}$$

Subtracting 1 and multiplying by 100 yields

$$\text{increase in sound speed} = 455.13\sqrt{\frac{\gamma_w}{M_w}} - 100 \tag{14}$$

Eq. (14) is plotted in Fig. 4 as a function of relative humidity for six temperature values. Fig. 4 shows the percentage increase in sound speed due to relative humidity only; the temperature values are for accurately specifying the relative humidity. Table 2 gives calculated results for Eq. (14).

Table 1. Velocity of sound in dry air versus temperature.

Temperature (°C)	Temperature (°F)	Velocity (m/s)	Velocity (ft/s)
0	32.0	331.45	1087.42
1	33.8	332.06	1089.42
2	35.6	332.66	1091.39
3	37.4	333.27	1093.39
4	39.2	333.87	1095.36
5	41.0	334.47	1097.33
6	42.8	335.07	1099.30
7	44.6	335.67	1101.26
8	46.4	336.27	1103.23
9	48.2	336.87	1105.20
10	50.0	337.46	1107.14
11	51.8	338.06	1109.11
12	53.6	338.65	1111.04
13	55.4	339.25	1113.01
14	57.2	339.84	1114.95
15	59.0	340.43	1116.88
16	60.8	341.02	1118.82
17	62.6	341.61	1120.75
18	64.4	342.20	1122.69
19	66.2	342.78	1124.59
20	68.0	343.37	1126.53
21	69.8	343.96	1128.46
22	71.6	344.54	1130.37
23	73.4	345.12	1132.27
24	75.2	345.71	1134.20
25	77.0	346.29	1136.11
26	78.8	346.87	1138.01
27	80.6	347.45	1139.91
28	82.4	348.02	1141.78
29	84.2	348.60	1143.69
30	86.0	349.18	1145.59
31	87.8	349.75	1147.46
32	89.6	350.33	1149.36
33	91.4	350.90	1151.23
34	93.2	351.48	1153.13
35	95.0	352.05	1155.00
36	96.8	352.62	1156.87
37	98.6	353.19	1158.74
38	100.4	353.76	1160.61
39	102.2	354.32	1162.45
40	104.0	354.89	1164.32

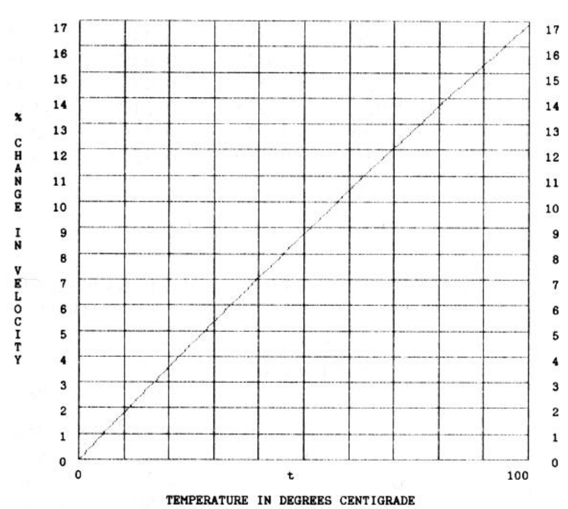

Fig. 3. Temperature versus percentage change in speed of sound (re 0°C) in dry air.

2.5 Combined Effects of Temperature and Relative Humidity

The results graphed in Figs. 3 and 4, and also tabulated in Tables 1 and 2, can be added together to show the combined effects of temperature and relative humidity on the speed of sound. Doing so produces Table 3. Here the total percentage increase in sound speed is tabulated for easy reference.

3 EFFECT OF RELATIVE HUMIDITY ON THE ABSORPTION OF SOUND IN AIR

3.1 Introduction

To a certain degree everything absorbs sound, especially air. Wet air absorbs sound better than dry air. This section presents the latest findings on the absorption of sound in air. The data are summarized in tables and graphs to highlight the effect of changing relative humidity on air absorption.

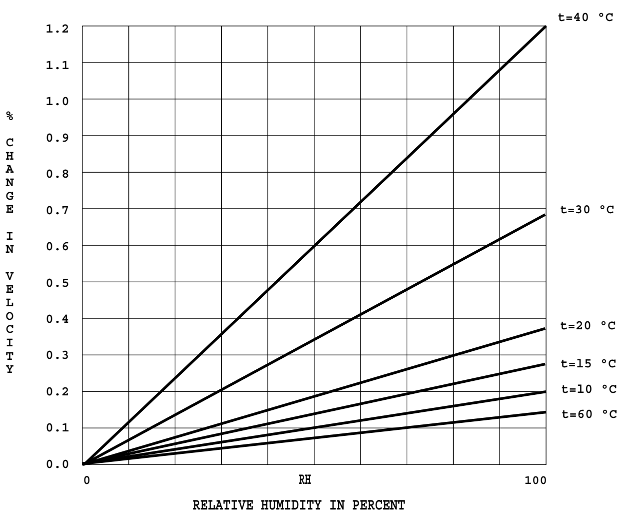

Fig. 4. Relative humidity versus percentage change in speed of sound as a function of temperature.

3.2 Air Absorption

Sound propagates through air as a wave in an elastic medium. Since air is not a perfectly elastic medium, this pulsating action causes several complex irreversible processes to occur. The wave action of air causes minute turbulence of the air molecules through which it passes. Each affected molecule robs the wave of some of its energy until eventually the wave dies completely. If this were not so, every sound generated would travel forever and we would live within a sonic shell of cacophony.

Absorption works with divergence. Divergence of sound causes a reduction in the sound intensity due to spreading of the wave throughout the medium. The sound pressure level will decrease 6 dB for each doubling of the distance, that is, it is inversely proportional to the square of the distance. This well-known fact occurs simultaneously with absorption. Absorption describes the energy-exchanging mechanism occurring during divergence. So not only is the wave spreading, it is also dying.

3.3 Air Absorption Mathematics

The strict confines of the ideal fluid-dynamic equations cannot explain the attenuation of sound. Theoretical predictions must include bulk viscosity, thermal conduction, and molecular relaxation for agreement with measured results. Conservation of mass, entropy for the gas, and molecular vibrations all enter into the thermodynamic equilibrium equations. To truly understand all the mechanisms of sound absorption in air, the interested reader must be ready to study molecular

Table 2. Percentage increase in speed of sound (re 0 °C) due to moisture in air only. Temperature effects not included except as they pertain to humidity.

Temperature (°C)	Relative humidity (%)									
	10	20	30	40	50	60	70	80	90	100
5	0.014	0.028	0.042	0.056	0.070	0.083	0.097	0.111	0.125	0.139
10	0.020	0.039	0.059	0.078	0.098	0.118	0.137	0.157	0.176	0.196
15	0.027	0.054	0.082	0.109	0.136	0.163	0.191	0.218	0.245	0.273
20	0.037	0.075	0.112	0.149	0.187	0.224	0.262	0.299	0.337	0.375
30	0.068	0.135	0.203	0.272	0.340	0.408	0.477	0.546	0.615	0.684
40	0.118	0.236	0.355	0.474	0.594	0.714	0.835	0.957	1.08	1.20

Table 3. Total percentage increase in speed of sound (re 0 °C) due to temperature and humidity combined.

Temperature (°C)	Relative humidity (%)					
	0	30	40	50	80	100
5	0.91	0.952	0.966	0.980	1.02	
10	1.81	1.87	1.89	1.91	1.97	2.01
15	2.71	2.79	2.82	2.85	2.93	2.98
20	3.60	3.71	3.75	3.79	3.90	3.98
30	5.35	5.55	5.62	5.69	5.90	6.03
40	7.07	7.43	7.54	7.66	8.03	8.27

kinetics, vibrational relaxation processes, and Navier-Stokes equations, and must know what a Laplacian is. Complete linear acoustic equations are not for the fainthearted. The mathematically courageous should refer to Pierce [4], where a painstakingly rigorous presentation is available.

Fortunately a simplified, yet accurate, alternate path exists. All of the above effects will combine into a term labeled total *attenuation coefficient* and designated by the letter m. This term is frequency, temperature, and humidity dependent [5]. For the case of a plane traveling wave, the following relationship holds [6]:

$$P = P_0 e^{-mx/2} \qquad \textbf{(15)}$$

where P_0 is the pressure amplitude at distance $x = 0$, m is the total attenuation coefficient, and P is the pressure amplitude at distance x. Fig. 5 shows values of the total attenuation coefficient m versus relative humidity for air at 20°C and normal atmospheric pressure for frequencies between 2 and 12.5 kHz [7].

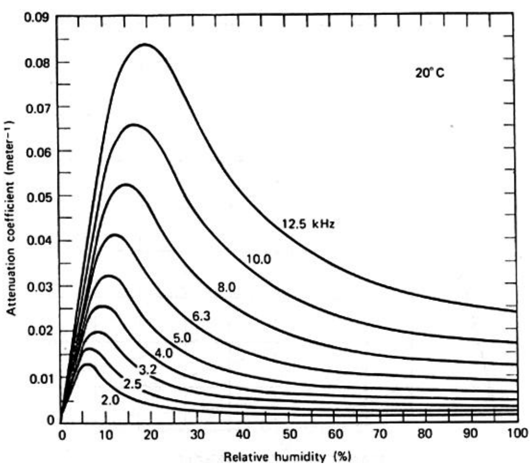

Fig. 5. Total attenuation coefficient *m* versus relative humidity for air at 20°C (68°F) as a function of frequency. From [7, p. 148].

Use Eq. (15) to obtain a direct expression relating loss in sound pressure level due to absorption. Dividing both sides by the reference pressure gives the ratio of the two pressures. Multiplying 20 times the log of both sides gives the sound pressure level (SPL) in decibels. Substituting a reference distance of 1000 ft (300 m) yields

$$\text{SPL loss in dB/1000 ft} = 20 \log e^{-500m} \qquad \textbf{(16)}$$

where m derives from Fig. 5. Eq. (16) is accurate to within 1 or 2 dB per 1000 ft (300 m) compared with experimental results.

3.4 Experimental Results

An extensive compilation of sound absorption values versus relative humidity exists in Evans and Bass [8]. An abstract of this report appears in [3, pp. E-45 to E-48]. A summary of the most relevant frequencies for sound reinforcement is given in Tables 4 and 5.

Note that the first column gives the absorption figures for dry air. By subtracting out the dry air figures, new tables result which show only the increase in sound absorption due to relative humidity (Tables 6 and 7). Figs. 6 and 7 graph the information in Tables 6 and 7 to show the overall shape of the absorption curves. Comparison with Fig. 5 shows the expected similarity of curve shapes. (Figs. 6 and 7 are straight-line approximations to the continuous curve for the points given in Tables 6 and 7. Many more points would be necessary to show the smooth shape accurately.)

Table 4. Total sound absorption in dB/1000 ft (300 m) versus relative humidity as a function of frequency at 20°C (68°F).

Frequency (kHz)	Relative humidity (%)										
	0	10	20	30	40	50	60	70	80	90	100
2	1.26	11.7	5.31	3.33	2.54	2.18	2.00	1.92	1.89	1.89	1.92
4	2.70	31.0	19.0	11.9	8.52	6.75	5.71	5.06	4.63	4.34	4.14
6.3	4.54	47.1	41.2	27.6	20.0	15.6	13.0	11.2	9.98	9.10	8.45
10	8.01	61.6	79.7	62.5	47.4	37.5	31.0	26.6	23.5	21.1	19.4
12.5	10.9	68.1	103	89.7	70.9	57.0	47.5	40.8	35.9	32.3	29.5
16	15.9	76.2	130	129	108	89.6	75.5	65.2	57.6	51.8	47.2
20	23.0	85.6	156	172	155	133	114	99.4	88.1	79.4	72.5

Table 5. Total sound absorption in dB/km versus relative humidity as a function of frequency at 20°C (68°F).

Frequency (kHz)	Relative humidity (%)										
	0	10	20	30	40	50	60	70	80	90	100
2	4.14	38.2	17.4	10.9	8.34	7.14	6.55	6.28	6.19	6.21	6.29
4	8.84	102	62.3	38.9	28.0	22.2	18.7	16.6	15.2	14.2	13.6
6.3	14.9	154	135	90.6	65.6	51.3	42.5	36.7	32.7	29.8	27.7
10	26.3	202	261	205	155	123	102	87.3	77.0	69.3	63.5
12.5	35.8	224	338	294	232	187	156	134	118	106	96.6
16	52.2	250	428	423	355	294	248	214	189	170	155
20	75.4	281	511	564	508	435	374	326	289	261	238

3.5 Observations

Several important observations result from an examination of Figs. 6 and 7, the most obvious being that there is a critical range of relative humidity occurring between 10 and 40%. Within this range, the increase in sound absorption is greatest. This range also represents the most common relative humidity encountered. The steepness of the curves about this critical range with their rapid rate of change is very startling. Just a 10% change in relative humidity, from 10 to 20% for instance, at a frequency of 12.5 kHz results in an additional 35 dB per 1000 ft (300 m) of absorption. 1000 ft (300 m) may seem excessive, but that is an additional 3.5 dB per 100 ft (30 m), which could alter the acoustic response significantly. It could be the difference between two identical concerts, where one sparkles and has more brilliance than the other. Yet the same orchestra performed them in the same hall with the same exuberance and skill-only the weather was different.

This same increase in absorption will also cause a substantial decrease in reverberation time in auditoriums where surface absorption is low [9]. For very large halls with highly reflecting surfaces, air absorption at high frequencies can be the dominant phenomenon, and the change in absorption due to relative humidity can be the dominant factor determining whether a concert is spectacular or dull.

For frequencies below 2 kHz, sound absorption due to relative humidity is not significant and is ignored. For room sizes less than about 200,000 ft^3 (5400 m^3)

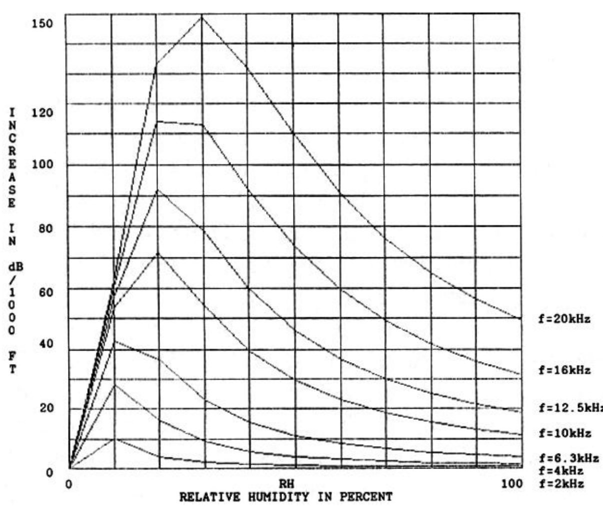

Fig. 6. Sound absorption increase in dB/l000 ft (300 m) versus relative humidity as a function of frequency at 20°C (68°F).

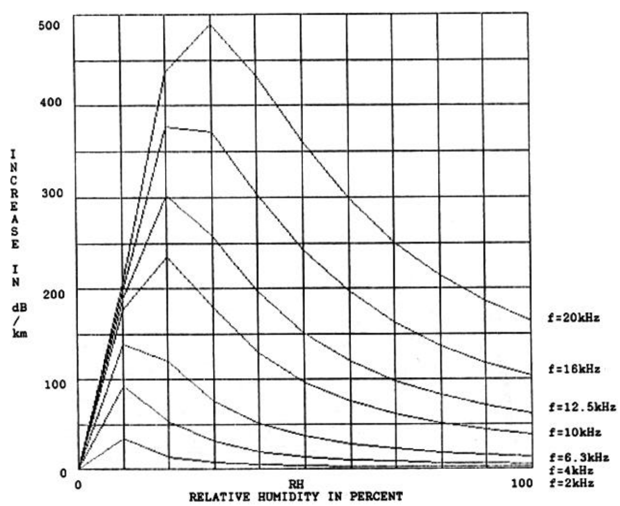

Fig. 7. Sound absorption increase in dB/km versus relative humidity as a function of frequency at 20°C (68°F).

Table 6. Increase in sound absorption in dB/l000 ft (300 m) due to relative humidity as a function of frequency at 20°C (68°F).

Frequency (kHz)	Relative humidity (%)										
	5	10	20	30	40	50	60	70	80	90	100
2	13.9	10.4	4.05	2.07	1.28	0.92	0.74	0.66	0.63	0.63	0.66
4	20.0	28.3	16.3	9.20	5.82	4.05	3.01	2.36	1.93	1.64	1.44
6.3	21.7	42.6	36.7	23.1	15.5	11.1	8.46	6.66	5.44	4.56	3.91
10	22.8	53.6	71.7	54.5	39.4	29.5	23.0	18.6	15.5	13.1	11.4
12.5	23.4	57.2	92.1	78.8	60.0	46.1	36.6	29.9	25.0	21.4	18.6
16	24.4	60.3	114	113	92.1	73.7	59.6	49.3	41.7	35.9	31.3
20	25.7	62.6	133	149	132	110	91.0	76.4	65.1	56.4	49.5

Table 7. Increase in sound absorption in dB/km due to relative humidity as a function of frequency at 20°C (68°F).

Frequency (kHz)	Relative humidity (%)										
	5	10	20	30	40	50	60	70	80	90	100
2	45.7	34.1	13.3	6.76	4.20	3.00	2.41	2.14	2.05	2.07	2.15
4	65.6	93.2	53.5	30.1	19.2	13.4	9.86	7.76	6.36	5.36	4.76
6.3	71.2	139	120	75.7	50.7	36.4	27.6	21.8	17.8	14.9	12.8
10	74.7	176	235	179	129	96.7	75.7	61.0	50.7	43.0	37.2
12.5	77.2	188	302	258	196	151	120	98.2	82.2	70.2	60.8
16	79.8	198	376	371	303	242	196	162	137	118	103
20	84.6	206	436	489	433	360	299	251	214	186	163

such as 100 by 100 by 20 ft (30 by 30 by 6 m)] sound absorption will not appreciably affect the *direct* sound. On the other hand, *reflected* sound covering great distances is affected, even in smaller rooms, that is, the reverberant sound field is more vulnerable than the direct sound field due to the distances involved.

4 SUMMARY

Environmental effects change the velocity and the absorption of sound in air. Even seemingly small percentage changes may cause serious listening problems in enclosed acoustic spaces. If room alignments down to tenths of an inch are to be meaningful, temperature and humidity should be controlled tightly.

Fractional changes in the wavelengths of frequencies traveling thousands of cycles can easily result in 180° phase reversal upon arrival. *No matter how small the change in the temperature, no matter how slight the humidity shift, the waves arrive shifted in phase and the resultant combination differs from the original.* It will not be the way it was when the room was equalized. Not only will the waves' phase be shifted, but for higher frequencies their magnitudes will be different due to the changes in absorption.

Much time is spent developing and using incremental time-delay devices to correct pictures shown by TDS instrumentation. An equal time spent in understanding and controlling the effects presented here is now required. The use of time-delay tools is valid, but remember, the implicit assumption being made is that the speed of sound does not change. Without rigid environmental controls this is a false assumption.

5 REFERENCES

[1] Based on R. B. Lindsay, "Historical Introduction," in J. W. S. Rayleigh, Ed., *The Theory of Sound* (Dover, New York, 1945).

[2] H. C. Hardy, D. Telefair, and W. H. Pielemeier, "The Velocity of Sound in Air," *J. Acoust. Soc. Am.*, vol. 13, pp. 226-233 (1942 Jan.).

[3] *CRC Handbook of Chemistry and Physics,* 67th ed. (CRC Press, Boca Raton, FL, 1986).

[4] A. D. Pierce, *Acoustics: An Introduction to Its Physical Principles and Applications* (McGraw-Hill, New York, 1981).

[5] L. B. Evans, H. E. Bass, and L. C. Sutherland, "Atmospheric Absorption of Sound: Theoretical Predications," *J. Acoust. Soc. Am.*, vol. 51, pp. 1565-1575 (1972).

[6] V. 0. Knudsen and C. M. Harris, *Acoustical Designing in Architecture* (Wiley, New York, 1950). p. 158.

[7] C. M. Harris, "Absorption of Sound in Air versus Humidity and Temperature," *J. Acoust. Soc. Am.*, vol. 40, pp. 148-159 (1966).

[8] L. B. Evans and H. E. Bass, "Tables of Absorption and Velocity of Sound in Still Air at 68°F (20°C)," AD-738576, National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22151.

[9] F. W. White, *Our Acoustic Environment* (Wiley, New York, 1975). pp. 447-450.

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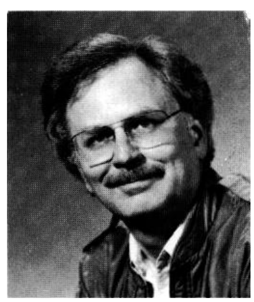

Dennis A. Bohn was born in San Fernando, California, in 1942. He received B.S.E.E. and M.S.E.E. degrees from the University of California at Berkeley in 1972 and 1974, respectively. Between undergraduate and graduate schools, he worked as a research and development engineer for the Hewlett-Packard Company developing thin-film high-speed oscillators. Upon completion of his M.S.E.E., he accepted a position with National Semiconductor Corporation as a linear application engineer specializing in audio. While at National Semiconductor, he created the *Audio Handbook*, acting as technical editor and contributing author. In 1976, he accepted the position of senior design engineer for Phase Linear Corporation, where he was involved in designing several consumer audio products. Promoted to engineering manager in 1978. he was responsible for developing the professional audio products division.

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