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Ambient Atmospheric Conditions and their Influence on Acoustic Measurements

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ABSTRACT

The paper describes an area that is often not considered by those who are involved in performing acoustic measurements. Specifically, the measured sound pressure level is directly influenced by the ambient atmospheric conditions in which the measurement is performed and by the raw condition of the device under test. The influence of temperature, atmospheric pressure and humidity are described. Different strategies for removing these influences are presented. Furthermore, consequences of ignoring these influences in the laboratory and on the production line are illustrated in terms of measurement error, falling yield and misalignment of sensitivity in active systems. The paper focuses on indoor acoustic measurements but the subject is equally valid for outdoor measurements.

1. INTRODUCTION

In the vast majority of acoustic measurements made, the measurement system and microphone are calibrated with a pistonphone prior to a number of measurements being performed. Additionally a golden device or reference unit is often used for calibration of the measurement system in a production environment - particularly in moving coil loudspeaker production. Generally we assume (but hopefully specify) that laboratory measurements are performed with *nominal* ambient atmospheric conditions that are at least within the IEC 60268-1 stated window for climatic conditions. Measurements in loudspeaker production, on the other hand, are done in whatever ambient conditions the factory presents.

In practice, this leaves us with several points of uncertainty and sources of variation, namely:

- The influence of different ambient conditions even within the IEC 60268-1 window in the laboratory.
- The influence of ambient changes following the moment of calibration in the laboratory.
- The influence of widely varying ambient conditions on the production line.
- The influence of the raw condition of the Device Under Test (DUT).
- How to compare measurements across larger time intervals.

Our desire some years ago for narrow End Of Line (EOL) target windows, that pushed the limits for what is commonly possible in acoustic measurements, led to an analysis of tolerances in the acoustic measurements we perform and subsequently a study of meteorological data for our development and production sites.

Interestingly, although the underlying physics of the subject of this paper are simple, it seems that the specific subject has not previously clearly been described in the literature in the context of acoustic measurements and particularly in loudspeaker production. Furthermore, engineers, manufacturers and the like generally fail to take account of the factors described here – or are simply unaware of them.

1.1. A Note on Microphone Calibration

For clarity, the method of calibrating a microphone with a pistonphone utilizes a small sealed cavity of fixed volume driven by a piston. This method of calibration is very insensitive to changes in ambient atmospheric conditions, such that a typical high-grade pistonphone will produce 94.0+/-0.2dB SPL in the cavity in the range of atmospheric conditions encountered.

It is important to note though, that calibrating a microphone in a measurement system only tells the system (from the capsule onwards) what level it should display or record for a given vibration of the microphone diaphragm. Calibrating a microphone in this way does not tell the measurement system anything about the actual transmission from DUT to microphone or DUT itself. Regular calibration of microphones with pistonphones in a fixed measurement set-up therefore gives a false sense of security as, in practice, the microphone capsule, pre-amplifier and subsequent electrical signal chain in reasonable quality test equipment is the most stable part of the entire measurement chain. Indeed modern instrument microphones are *extremely* stable.

Also, touching the microphone when mounting and removing a calibrator is likely to cause damage and/or shift the physical position of the capsule which will have a larger influence on measurements than not calibrating the microphone. Of-course, using a calibrator when setting test equipment up, or following physical/electrical modifications, is strongly desirable, as the sound pressures measured are most interpretable if in dB SPL (dB relative to 20μPa).

Consider the following scenario: A manufacturer is producing active loudspeakers to a specified sensitivity with the intention that all loudspeakers sold have the same sensitivity. Two “imaginary” loudspeakers that are identical in every respect are tested on consecutive days with different ambient atmospheric pressure. Although the microphone was calibrated prior to each measurement, the loudspeakers will produce different sound pressures at the microphone simply due to the change in atmospheric pressure – with the result that, at least one of the loudspeakers will be adjusted to the wrong output.

2. ATMOSPHERIC INFLUENCES

Wherever we perform acoustic measurements in the world, we are surrounded by meteorological conditions or weather. Weather describes the varying ambient atmospheric conditions in which we are surrounded. If we consider performing acoustical measurements in air, without the influence of wind and precipitation, then these varying ambient atmospheric conditions can be defined by three parameters:

- Atmospheric pressure
- Temperature
- Relative humidity

The influences of these three parameters are described in the following sections.

2.1. Influences on Sound Pressure

In order to see the relationship between the sound pressure *p* radiating from a sound source and the atmospheric pressure and temperature, consider the well-known equation for the radiation of a diverging harmonic wave from a point source [1, 2]:

$$\hat{p} = \frac{j\omega\rho Q}{4\pi r} e^{j(\omega t - kr)} \tag{1}$$

Similarly for a piston in an infinite rigid baffle in the far-field:

$$\hat{p} = \frac{j\omega\rho Q}{2\pi r} e^{j(\omega t - kr)} \tag{2}$$

Disregarding the terms that are not dependent on the properties of the transmission medium (air) we see that the sound pressure in both cases is directly proportional to the density of the air:

$$p \propto \rho \tag{3}$$

We will assume at first that our transmission medium between the sound source and microphone is dry air without the presence of water vapour (the influence of humidity is considered separately later). In this case, the density of air is given by the ideal gas law relating the density to the atmospheric pressure *P*, the absolute temperature *T*, and for dry air; the molar mass *M* (0.02896kg·mol^{-1}) and the ideal gas constant *R* (8.315J·mol^{-1}·K^{-1}):

$$\rho = \frac{MP}{RT} \tag{4}$$

Substituting equation (4) in (3) we see that:

$$p \propto \frac{P}{T} \tag{5}$$

Therefore, the sound pressure radiated through the air is directly proportional to the atmospheric pressure and inversely proportional to the absolute temperature. In other words;

- As the atmospheric pressure increases (more air molecules in the transmission path) the sound pressure increases.
- As the temperature increases (fewer air molecules in the transmission path) the sound pressure decreases.

Relationship (5) above can be split into the two ambient parameters; ambient atmospheric pressure and absolute temperature, and their influence expressed individually in decibels for a change from a start ambient condition (P_1 or T_1) to end ambient condition (P_2 or T_2):

$$\Delta p_P = 20\log_{10}\left[\frac{P_2}{P_1}\right] \tag{6}$$

And:

$$\Delta p_T = 20\log_{10}\left[\frac{T_1}{T_2}\right] \tag{7}$$

It is important to highlight that the influences of ambient atmospheric pressure and temperature described above **directly** influence the *transmitted* sound pressure from a source. Additionally however, for moving coil loudspeakers, the ambient temperature also has an **indirect** effect on the measured sound pressure as changes in ambient temperature also influence the sound pressure generated by the loudspeaker.

In other words, the sensitivity of a moving coil loudspeaker is directly influenced by the temperature of the coil. This change in sensitivity in decibels with temperature from an ambient temperature T_1 to T_2 is related to the resistance of the coil R_e and is given by:

$$\Delta S = 20\log_{10}\left[\frac{R_e(T_1)}{R_e(T_2)}\right] \tag{8}$$

This can be expressed in terms of the temperature coefficient of the voice coil material α by:

$$\Delta S = 20\log_{10}\left[\frac{1}{1+\alpha(T_2 - T_1)}\right] \tag{9}$$

Therefore, as the ambient temperature increases ($T_2 > T_1$) the sensitivity of a moving coil loudspeaker decreases.

It is important to note, that for moving coil loudspeakers that are at the ambient temperature in which a sound pressure measurement is performed, then the effect described in equation (7) and (9) will be correlated and must therefore be **added**.

Finally, we must consider the influence of humidity. The influence of humidity in the air on the transmission of sound has been studied for decades [3]. The results of this work have been standardized by the International Standards Organisation who has published a method of calculation of the attenuation of sound due to humidity in the atmosphere [4]. The influence of humidity in the air is of course well-known as attenuating the sound travelling through it, particularly at high frequencies. The formulae from the standard will not be reproduced here as they are lengthy; however it is worth noting that the calculation of attenuation due to humidity for a given distance is dependent on four parameters:

- Atmospheric pressure
- Temperature
- Relative humidity
- Frequency

Generally; absorption increases with frequency, for a given frequency will have its maximum attenuation in the range 5 to 40% relative humidity, and the effect on absorption of changing atmospheric pressure in the range that will be described later in this paper is negligible. Figure 1 and table 1 illustrate absorption due to humidity in dB/m at 20^{o}C and 1013.25hPa for a selection of frequencies in the upper audible range.

We can conclude that the attenuation from humidity will become great at high frequencies over large distances, which is a common challenge in public address in large venues. However, if we are concerned with acoustic measurements in the laboratory or in a production environment, then two factors significantly reduce the attenuation figures indicated above, namely;

1) The measurement distance is typically ≤1m and often production measurements are performed in test chambers at distances of only 10 to 40cm.

2) It is the change in attenuation due to humidity at a given frequency that is of interest and thus in practice, will be dependent upon the actual range of ambient atmospheric conditions encountered at the measurement site, and the rate of change of these.

The influence of humidity will be further described in sections 3 and 4 when information about the actual atmospheric variations is presented.

Frequency (Hz)	Attenuation (dB/m)	Maximum at (%RH)
2500	≤ 0.07	7
5000	≤ 0.14	12
10000	≤ 0.28	19
20000	≤ 0.60	32

Table 1 Typical values for absorption due to humidity at 20^{o}C and 1013.25hPa for the four frequencies indicated

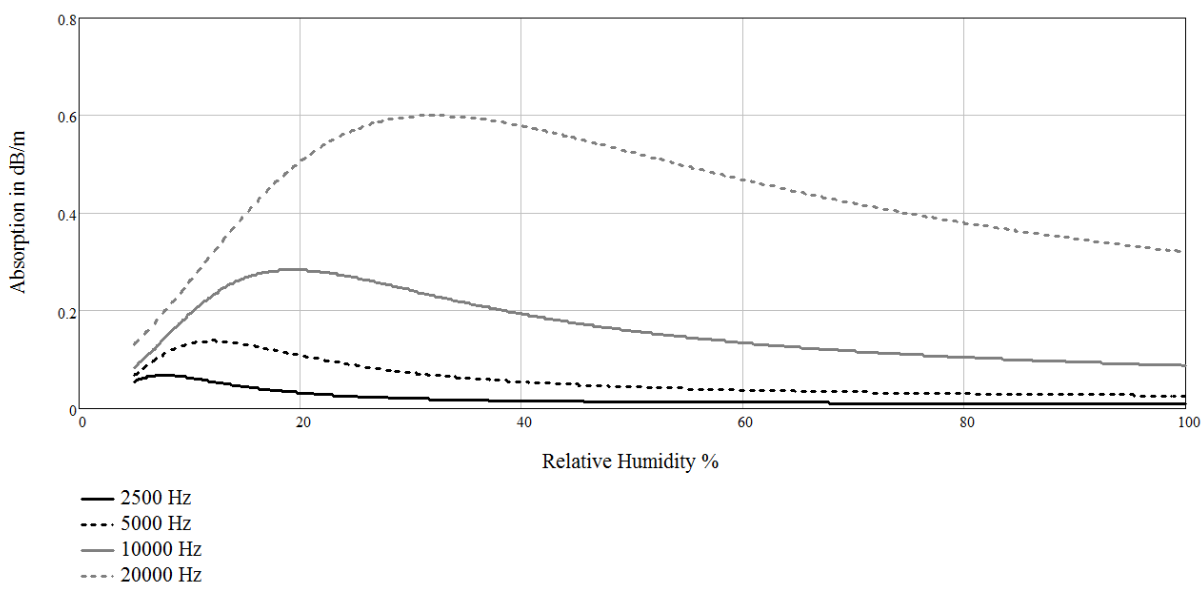

Figure 1 Absorption against relative humidity at 20^{o}C and 1013.25hPa for the four frequencies indicated

2.2. Influences on Sound Power

As a note of interest, let us consider the sound power W generated by a point source [1, 2] which can be calculated from the radiation impedance Z:

$$W = \frac{1}{2}|Q|^2 \operatorname{Re}\{Z\} = \frac{\rho c |Q|^2}{4\pi a^2} \propto \rho c \qquad (10)$$

The sound power from the point source is therefore proportional to the impedance of air.

The speed of sound c, where γ is the adiabatic index or ratio of specific heats, for an ideal gas is determined by the well-known formula:

$$c = \sqrt{\frac{\gamma P}{\rho}} \qquad (11)$$

It can be concluded from the data presented by Dean [5] and Zacherwar [6] among others, that the deviation of the speed of sound given by the ideal gas law in real air conditions within the range of temperatures, humidity's and atmospheric pressures encountered near sea level when we could be in the medium ourselves performing acoustic measurements, will be within +/-0.2%. It will be seen that this error is quite insignificant compared to the other variations involved.

Combining equations (4) and (11) we find:

$$\rho c = \rho \sqrt{\frac{\gamma P}{\rho}} = \frac{MP}{RT}\sqrt{\frac{\gamma RT}{M}} \propto \frac{P}{\sqrt{T}} \qquad (12)$$

From equations (10) and (12) we can conclude that:

$$W \propto \frac{P}{\sqrt{T}} \qquad (13)$$

Thus, the sound power radiated from a point source is directly proportional to the ambient atmospheric pressure and inversely proportional to the square root of the absolute temperature. Relationship (13) above can be split into the two ambient parameters; ambient atmospheric pressure and absolute temperature, and their influence expressed individually in decibels for a change from a start ambient condition (P_1 or T_1) to end ambient condition (P_2 or T_2):

$$\Delta W = 10 \log_{10}\left[\frac{P_2}{P_1}\right] \qquad (14)$$

$$\Delta W = 5 \log_{10}\left[\frac{T_1}{T_2}\right] \qquad (15)$$

Acousticians may have come across these two equations when working with calibrated sources of sound power.

3. INFLUENCE WITHIN IEC 60286-1

The IEC standard 60268-1 [7] states a range of climatic conditions for the purpose of standardizing the conditions in which measurements relating to sound system equipment are performed with the aim of reducing the possible influence of the ambient climatic conditions such that measurements made across different sites and times are more comparable. The following ranges are stated:

- Atmospheric pressure 860 to 1060hPa (mbar)
- Temperature 15^{o}C to 35^{o}C, preferably 20^{o}C
- Relative humidity 25 to 75%

The influence on measured sound pressure for each of these parameters will now be calculated. From equation (6) the influence of atmospheric pressure changing from 860 to 1060hPa will be:

$$\Delta p_P = 20 \log_{10}\left[\frac{1060}{860}\right] = 1.82\ dB \qquad (16)$$

This is illustrated in figure 2 relative to a reference atmospheric pressure of 1013.25hPa. Similarly the influence from equation (7) for temperature changing from 15 to 35^{o}C, *noting that the temperatures in the formula are absolute temperatures in Kelvin*, will be:

$$\Delta p_T = 20 \log_{10}\left[\frac{273.15+15}{273.15+35}\right] = -0.58\ dB \qquad (17)$$

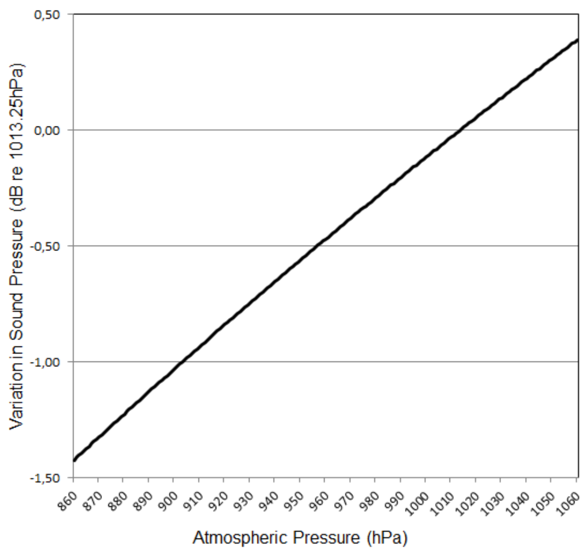

Figure 2 Variation in sound pressure due to varying atmospheric pressure within the IEC 60268-1 range.

Furthermore, for moving coil loudspeakers at the same temperature as (acclimatised to) the ambient conditions, the influence of this temperature range for copper and/or aluminium voice coils, from equation (9), will be:

$$\Delta S = 20\log_{10}\left[\frac{1}{1+0.0039(20)}\right] = -0.65\,dB \qquad (18)$$

The two effects of temperature here are correlated and must be added. Therefore the total influence of temperature alone in the range stated will be -1.23dB. This is illustrated in figure 3 which shows both the individual influences of transmission (dashed) and sensitivity (dotted) and the total deviation (solid) relative to a reference temperature of 20^{o}C.

On first impression, when comparing figures 2 and 3, it may appear that the two effects cancel each other out, however the two influences are not related and therefore cannot be considered in this way. In-fact they can both contribute to a positive (or negative) change in sound pressure.

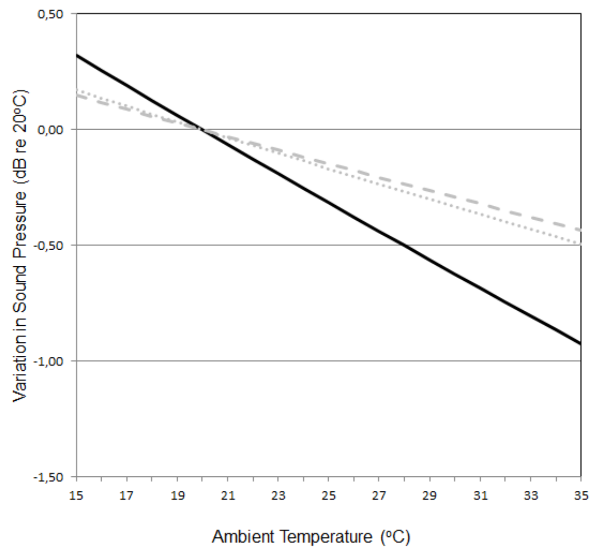

Figure 3 Variation in sound pressure due to varying ambient temperature within the IEC 60268-1 range.

The influence of changing humidity is slightly more complicated to calculate as it has to be seen combined with the pressure and temperature ranges above, however study based on [4] leads to the following results shown in table 2 for the atmospheric ranges stated in IEC 60268-1 and for selected frequencies in the upper audible range.

Frequency (Hz)	Attenuation change (dB/m)	Maximum at (%RH)
2500	≤ +/-0.01	25
5000	≤ +/-0.03	25
10000	≤ +/-0.06	34
20000	≤ +/-0.11	60

Table 2 Figures for the possible change in absorption due to humidity within IEC 60268-1

We can conclude that it is in theory possible to see a total variation in sound pressure level from a given loudspeaker in the range of climatic conditions stated in IEC 60268-1 of up to ~3dB when measured at a distance of 1m and all other tolerances are ignored. Note that the influence of pressure and temperature can be of equal sign for example, if pressure increases and temperature decreases as would be the case if measuring the same unit at 860hPa/35^{o}C and again at 1060hPa/15^{o}C (thus illustrating worst case).

In reality, this large window of atmospheric pressure is not experienced at a single site as will be described in section 4. The temperature window however, is quite realistic for different sites. The influence of humidity in the window stated is insignificant compared to the influence of atmospheric pressure and temperature in the audible frequency range.

4. OBSERVED VARIATIONS IN PRACTICE

This section will present the atmospheric variations seen in practice at a real production site in Denmark (25m above sea level, latitude 56^{o}). The data is recorded indoors in a large production area with ordinary heating and ventilation (ordinary air conditioning).

4.1. Variations in Atmospheric Pressure

Figure 4 shows the recorded atmospheric pressure at 15 minute intervals during 2013. The data reveals an average atmospheric pressure of 1011hPa indicated on the figure as the central dashed line. Also displayed are dotted lines enclosing 95% of readings or 1011+/-20hPa. Figure 5 shows a histogram of the data and it can be seen that the distribution approaches a skew normal distribution leaning to the lower pressures, which is typical of atmospheric pressure at this latitude.

Furthermore, it can be concluded that the average rate of change of atmospheric pressure is 0.5hPa/hour and that the rate of change in 95% of cases does not exceed 1.5hPa/hour. Variations in excess of 10hPa/hour where also recorded.

Considering also atmospheric pressure data from the Danish Meteorological Institute for a weather station in the town of Karup, close to the production location described here, then from 30 years of data from 1969 to 1999, the average atmospheric pressure was 1013hPa with a maximum at 1063hPa and a minimum at 944hPa.

For a production site of this location, it is possible to conclude the following regarding atmospheric pressure:

- 1011+/-20hPa represents ***typical*** variations (including 95% of time). From equation (6), this causes a sound pressure variation of +/-0.17dB.
- 1011+/-30hPa represents ***occasional*** variations (including 99.7% of time). From equation (6), this causes a sound pressure variation of +/-0.25dB.
- +50/-69hPa represents ***extreme*** variations. From equation (6), this causes a sound pressure variation of +0.42/-0.61dB.
- A ***typical*** rate of change does not exceed 1.5hPa/hour or ~0.01dB/hour.

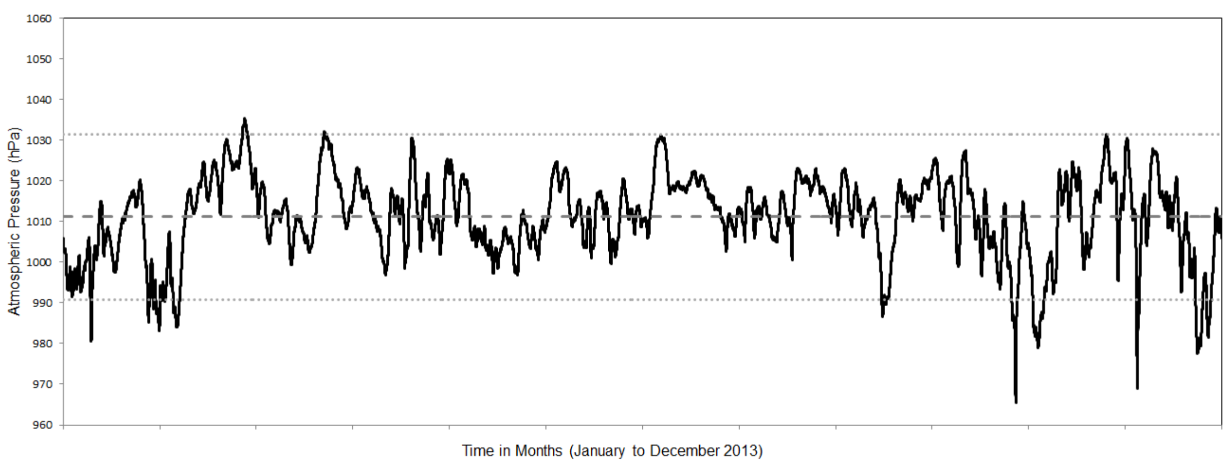

Figure 4 Atmospheric pressure recorded in 2013 for a production site in Denmark

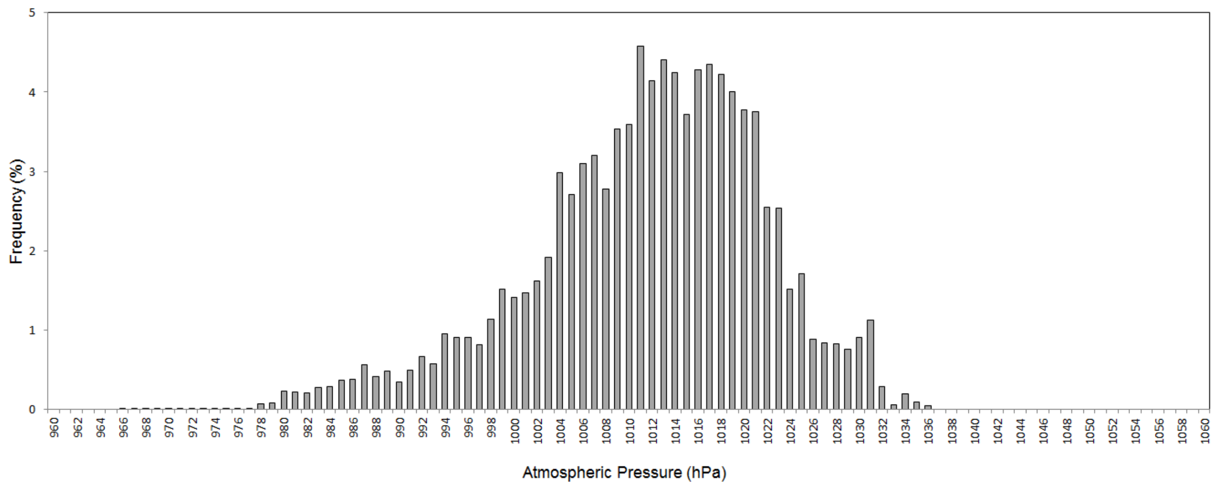

Figure 5 Distribution of the atmospheric pressure data in figure 4 in 1hPa bins with frequency of occurrence in %

- An ***occasional*** rate of change is 2hPa/hour or ~0.02dB/hour.

- An ***extreme*** rate of change is 10hPa/hour or ~0.09dB/hour.

The magnitudes of these sound pressure variations caused by atmospheric pressure are applicable, if the reference sound pressure or response (measurement system calibration with a golden device or reference loudspeaker to determine the target for running production) is made at an atmospheric pressure close to average for the location (~1011hPa in this case). They therefore reflect the smallest variations one can expect.

Consider the realistic scenario where a calibration at the above production site is performed at a time when the atmospheric pressure is 1031hPa (a day of high pressure). Typical variations will then only lie below this atmospheric pressure resulting in a deviation in sound pressure of +0.0/-0.34dB. In-fact, the sound pressure measured from approximately 5% of the ensuing production will deviate by more than 0.4dB during the year from the value at calibration.

If one were unfortunate enough to calibrate a system a day in October when the pressure is only 970hPa (deep low pressure), then approximately 95% of the ensuing production will deviate in sound pressure by between +0.18dB and +0.52dB simply due to the change in atmospheric pressure. If, with this unfortunate calibration, the target limits for a sensitivity adjustment in production are +/-0.25dB, then 90% of ensuing production at the above location will be out of specification.

It can be concluded that variations in atmospheric pressure can significantly influence production yield, *whether the manufacturer is aware of it or not!*

Furthermore, the data and considerations regarding atmospheric pressure are equally valid for indoor as well as outdoor acoustic measurements.

It is also worth noting that the variations in atmospheric pressure observed at this single location are significantly less than the IEC 60268-1 window. This is very likely because the IEC window was originally arranged to include locations around the world and at altitudes up to approximately 1000m above sea level.

4.2. Variations in Indoor Temperature

Figure 6 shows the indoor temperature at the acoustical test facilities recorded at 15 minute intervals during 2013. The data reveals an average temperature of 23.0^{o}C indicated on the figure as the central dashed line. Also displayed are dotted lines enclosing 95% of readings or 23.0+/-3.5^{o}C. Figure 7 shows a histogram of the data and it can be seen that the distribution approaches a skew normal distribution leaning to the higher temperatures.

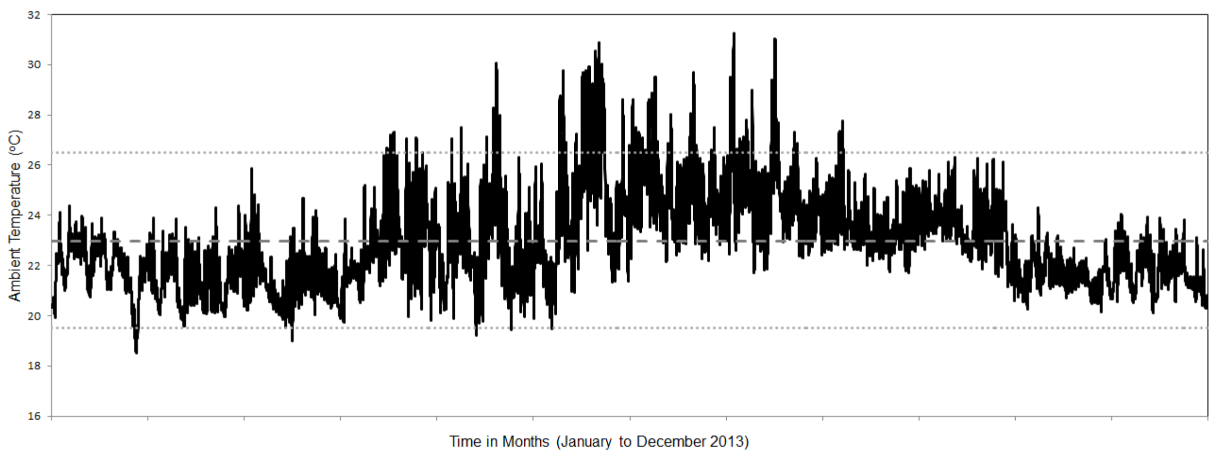

Figure 6 Indoor temperature recorded in 2013 for a production site in Denmark

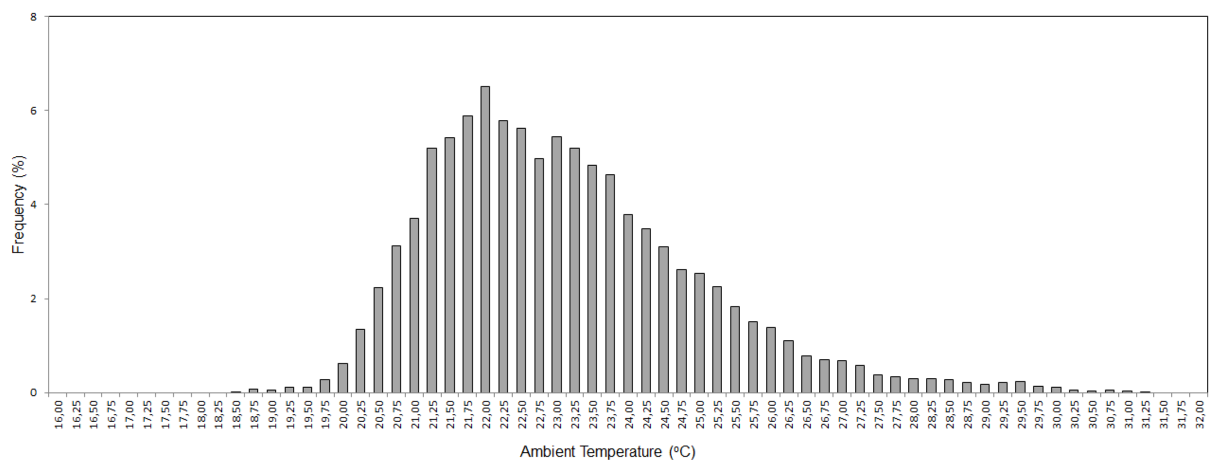

Figure 7 Distribution of the temperature data in figure 6 in 0.25°C bins with frequency of occurrence in %

Furthermore, it can be concluded that the average rate of change of indoor temperature is 0.3°C/hour and that the rate of change in 95% of cases does not exceed 1.0 °C/hour. Variations of 3°C/hour where also recorded.

For a production site of this location, it is possible to conclude the following regarding indoor temperature and its influence on transmission through the air:

- 23.0+/-3.5°C represents ***typical*** variations (95% of time). From equation (7), this temperature range causes a sound pressure variation of -/+0.10dB.
- 23.0+/-4.5°C represents ***occasional*** variations (99.7% of time). From equation (7), this causes a sound pressure variation of -/+0.13dB.
- +8.5/-4.5°C represents ***extreme*** variations. From equation (7), this causes a sound pressure variation of -0.25/+0.13dB.
- A ***typical*** rate of change does not exceed 1°C/hour or ~0.03dB/hour (of opposite sign).

- An ***extreme*** rate of change is 3^{o}C/hour or ~0.09dB/hour (of opposite sign).

Before any conclusions can be made about the influence of indoor temperature variations described above, we must also consider the indirect effect of temperature and its influence on the sensitivity of moving coil loudspeakers.

From equation (9), we can calculate that the variations in temperature described in this section will give the following variation in loudspeaker sensitivity (for copper and/or aluminium voice coils):

- Typical sensitivity variation of -/+0.12dB.
- Occasional sensitivity variation of -/+0.15dB.
- Extreme sensitivity variation of -0.28/+0.15dB.
- Typical rate of change ≤ 0.03dB/hour.
- Extreme rate of change is 0.1dB/hour.

As stated earlier, these two effects of temperature will be correlated and must be added for loudspeaker units that are acclimatised to the temperature in the production area. Therefore we will see (for transmission *and* sensitivity influences):

- ***Typical*** variation of -/+0.22dB.
- ***Occasional*** variation of -/+0.28dB.
- ***Extreme*** variation of -0.53/+0.28dB.
- ***Typical*** rate of change ≤ ~0.06dB/hour.
- ***Extreme*** rate of change of ~0.2dB/hour.

The magnitudes of these sound pressure variations due to indoor ambient temperature are applicable, if the reference sound pressure or response for a particular loudspeaker is recorded at a temperature close to average for the test area (~23^{o}C in this case). The figures above therefore reflect the smallest variations one can expect.

Consider the realistic scenario where a calibration at the above production site is performed with an acclimatised golden device an afternoon in the summer when the temperature is 30^{o}C. Typical total variations (from transmission and sensitivity) will then only lie below this temperature resulting in a deviation in sound pressure of +0.22 to +0.66dB. If in this example the target limits for a sensitivity adjustment in production are +/-0.25dB, then 51% of ensuing production at the above location will be out of specification.

It can be concluded, that even in reasonably well-controlled temperature conditions, variations in indoor ambient temperature can significantly influence production yield.

It can be noted that the variations in indoor temperature observed at this single location are slightly less that the IEC 60268-1 window. It would not however be realistic to have a narrower window if it is to encompass measurement environments around the world.

4.3. Variations in Outdoor Temperature

Those performing acoustic measurement outdoors can experience larger temperature changes than those described in section 4.2. For the location described in Denmark, the average outdoor temperature is 7.5^{o}C and is within +/-13^{o}C of this 95% of the time. Considering data from the Danish Meteorological Institute, then extreme variations in the outdoor temperature for this location are +/-25^{o}C. The typical night-to-day temperature difference is only 7^{o}C. This is of course a simple example of a well-behaved temperate climate. However, the outdoor temperature will play a role in our calculations if, for example, loudspeakers are moved from an unheated storage area or truck in winter into the production area or laboratory and are tested a short time thereafter. Now equation (9) must reflect the temperature of the un-acclimatised voice coil. Hence the contribution of transmission in equation (7) will not follow the change in sensitivity from equation (9).

Consider an example where a batch of subwoofers is moved into production from a truck at 0^{o}C. The units are only unpackaged just before test and therefore the copper voice coil is still at 0^{o}C. The measurement system has been calibrated with the golden device at normal test room temperature of 23^{o}C. The subwoofers from the truck will then measure 0.75dB louder than if they had been acclimatised to the test area conditions. Note that this simple example deliberately ignores all other effects (such as a stiffer suspension).

In outdoor environmental acoustics, relatively large temperature differences are required for the variation in sound pressure to become significant in, for example, typical environmental noise measurements. As an example, a -0.5dB change in sound pressure transmission through dry air due to temperature alone is given by a temperature change from 10 to 27°C.

4.4. Variations in Relative Humidity

Figure 8 shows the recorded relative humidity at 15 minute intervals during 2013. The data reveals an average relative humidity of 33% indicated on the figure as the central dashed line. Also displayed are dotted lines enclosing 95% of readings or 33%RH+/-16ppRH (pp - percentage points). Figure 9 shows a histogram of the data and it can be seen that the distribution is not normal, but is grouped between lower winter humidity's and higher summer humidity's. The highest recorded value in 2013 was 57% and the lowest value was 11%.

Furthermore, it can be concluded that the average rate of change of relative humidity is 0.6ppRH/hour (percentage points per hour) and that the rate of change in 95% of cases does not exceed 2.0ppRH/hour. Variations of 4ppRH/hour where also recorded.

Considering the whole range of relative humidity's recorded in 2013 and displayed in figure 8 (11 to 57%), we can analyse the influence of humidity by again calculating the absorption (as described in section 2.1.) across a range of frequencies and investigating the maximum change possible for given frequencies. Table 3 shows the largest change possible in absorption due to humidity in dB/m for the temperature range of 23.0+/-4.5°C and 1011+/-30hPa for a selection of frequencies in the upper audible range.

Frequency (Hz)	Attenuation change (dB/m)	Maximum at (%RH)
2500	≤ +/-0.01	12
5000	≤ +/-0.02	20
10000	≤ +/-0.07	11
20000	≤ +/-0.14	14

Table 3 Figures for the possible change in absorption due to humidity for the production site in Denmark

Furthermore, it can be calculated that the rate of change of absorption due to changing humidity at a rate of 2.0ppRH/hour for the stated production site will be less than 0.04dB/hour and never more than 0.28dB/m in total for frequencies up to 20kHz.

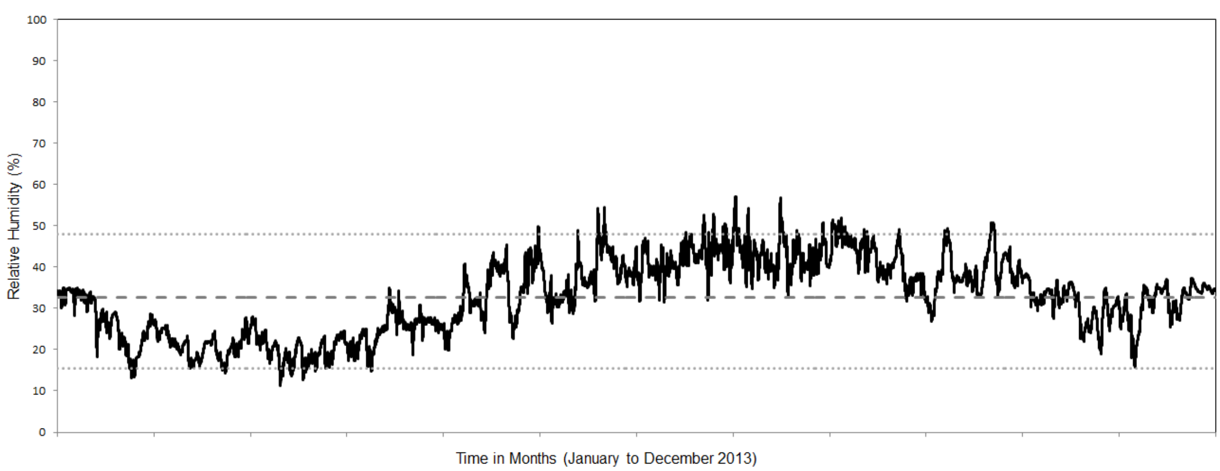

Figure 8 Relative humidity recorded in 2013 for a production site in Denmark

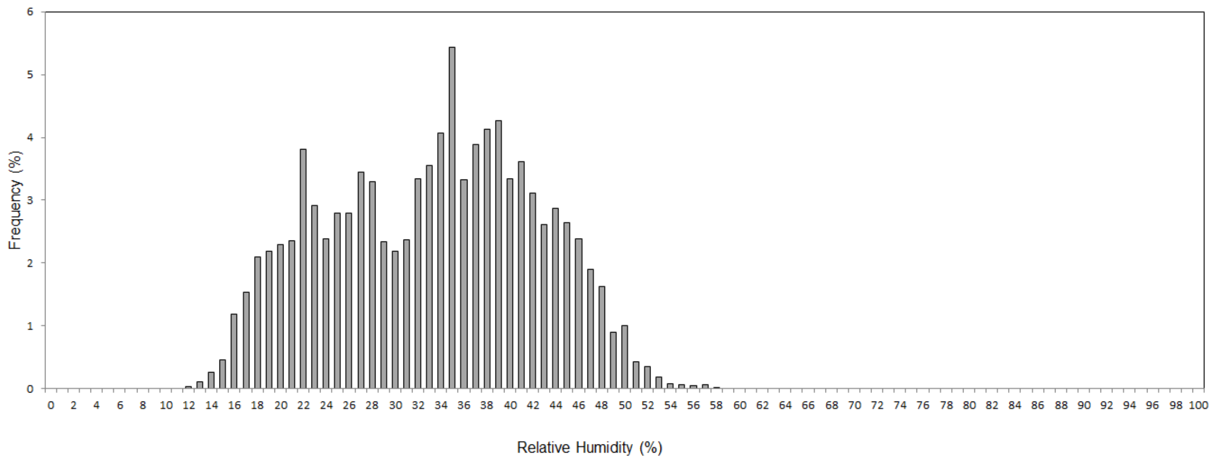

Figure 9 Distribution of the relative humidity data in figure 8 in 1% bins with frequency of occurrence in %

It can be concluded from the table that should we wish to include the variation possible due to changes in relative humidity for the production location presented, then this could be done by simply widening any test limits by 0.07dB per meter measurement distance at 10kHz increasing to 0.14 dB per meter measurement distance at 20kHz. Generally however, the influence of humidity for measurement distances used indoors is negligible and therefore neglected.

One point of interest is that some raw materials, such as those occasionally used in tweeter membranes, do absorb moisture from the air which consequently can affect the acoustical performance of the unit. This is a possible argument for recording the relative humidity data for the production site or in the laboratory even if the data is not immediately used for anything, but in hindsight could help in root-cause analysis.

Furthermore, the IEC 60268-1 window for relative humidity is unrealistic. The consequence of adhering rigidly to it requirements would mean that it would not be possible to perform measurements in most of January through March at the production site described here. To cover worldwide conditions, but still have *some* control, then 10 to 90% limits for relative humidity may be more appropriate.

5. OVERVIEW OF THE INFLUENCE OF AMBIENT ATMOSPHERIC CONDITIONS

Table 5 presents an overview of the influences caused by varying atmospheric conditions for a temperate climate such as Denmark as described in section 4.

5.1. Comparison with Other Sources of Measurement Tolerance

In order to put the influence of the different ambient atmospheric conditions into perspective, table 6 presents some other typical tolerances in a capable acoustical measurement system. These include the electrical signal path with microphone capsule and pre-amplifier, and the physical test set-up such as measurement distance and background noise.

Source of influence	Tolerance (dB)
Electrical signal path	+/-0.10
Measurement distance 50+/-0.5cm	+/-0.09
Background noise <-40dB	<+/-0.09
Microphone/preamplifier stability*	<+/-0.05

Table 6 Other typical measurement tolerances

*High quality measurement microphones typically have pressure coefficients of 0.001 dB/hPa and temperature coefficients of -0.006dB/^{o}C.

Source of influence	Typical	Occasional	Extreme
Atmospheric pressure	+/-20hPa or **+/-0.17dB**	+/-30hPa or **+/-0.25dB**	+50/-69hPa or **+0.42/-0.61**
Temperature (transmission only)	+/-3.5°C or **-/+0.10dB**	+/-4.5°C or **-/+0.13dB**	+8.5/-4.5°C or **-0.25/+0.13dB**
Temperature (sensitivity only)*	+/-3.5°C or **-/+0.12dB**	+/-4.5°C or **-/+0.15dB**	+8.5/-4.5°C or **-0.28/+0.15dB**
Temperature (transmission + sensitivity)*	+/-3.5°C or **-/+0.22dB**	+/-4.5°C or **-/+0.28dB**	+8.5/-4.5°C or **-0.53/+0.28dB**
Temperature (outdoor/storage only)*	+/-13°C or **-/+0.43dB**	+/-19.5°C or **-/+0.64dB**	+/-25°C or **-/+0.81dB**
Relative humidity	**≤ +/-0.14 dB/m** at ≤ 20kHz		

Table 5 Overview of the influences caused by the atmospheric conditions varying from nominal values for a temperate climate such as Denmark (the temperature coefficient used* was α=0.0039Ω/°C)

It is clear that the influence of varying ambient atmospheric conditions outweighs other typical tolerances in the measurement chain noticeably.

6. STRATEGIES FOR REDUCING THE INFLUENCE OF AMBIENT ATMOSPHERIC CONDITIONS

Three main strategies for reducing the influence of varying ambient atmospheric conditions are presented below in order of complexity. All of them will contribute to more accurate measurement results and hence more accurate data and more parts will be produced within specification (improved yield).

6.1. Acclimatisation of DUT

Simply acclimatising the DUT to the ambient conditions of the test area will remove the influence of sensitivity error described in equation (9) and illustrated in sections 4.2 and 4.3. Acclimatisation prior to measurement is equally valid in the laboratory and on the production line when bringing parts in from another climate such as storage or transport and following heating/baking processes on the assembly line. Table 7 below illustrates rule-of-thumb acclimatisation times in minutes for a range of **unpackaged** loudspeakers based on typical thermal time constants.

Ideally, raw parts and complete loudspeaker drive units should be stored on the production floor from the night before they are to be tested.

Loudspeaker Type	Temperature Difference Magnitude (°C)						
	30	15	12	9	6	3	0
Large Subwoofer	408	324	300	264	216	120	0
Woofer	204	162	150	132	108	60	0
Midrange	102	81	75	66	54	30	0
Tweeter	34	27	25	22	18	10	0

Table 7 Rule-of-thumb acclimatisation times in minutes for typical loudspeakers to achieve a temperature difference to the surroundings of less than 1°C.

6.2. Regular calibration with a Golden Device

Following acclimatisation of the DUT, the next improvement that can be made is to regularly re-calibrate the test equipment with a reference loudspeaker or golden device. The purpose of this is to reduce the influence of atmospheric variations by limiting the time passed from the last calibration where the transmission path was included in the calibration of the test equipment (calibration with a pistonphone does not solve this as described in the introduction).

The time interval between calibrations can be determined by considering the rate of change of the atmospheric parameters and the actual measurement tolerance of the relevant equipment. Ideally, the time interval should be chosen as being equal to when one would reasonably expect the change due to atmospheric conditions to equal the measurement tolerance of the system itself (and therefore the change is just detectable by the equipment). A useful rule-of-thumb for temperate climates is that changes will occur at a rate of 0.1dB/hour.

For example, if a measurement system itself has a tolerance of +/-0.4dB, then one could expect variations due to atmospheric changes to reach this level approximately every 4 hours.

It should be possible to program the test sequence to request recalibration with the golden device at the time interval specified during continuous production and also following a sequence change to another product (when typically the jig or baffle is interchanged if the equipment is used to test a range of loudspeakers).

It should be noted that golden devices should be kept secure but on the production floor – or at least under the same climatic conditions as the test equipment that they are used (otherwise acclimatisation is necessary each time the device is to be used).

6.3. Automatic (and manual) compensation

The ideal solution is to measure the atmospheric conditions locally (close to the test equipment) and automatically correct the measured sound pressure for the variations caused by the changing atmospheric conditions. It is necessary to record atmospheric pressure and temperature. The influence of humidity is negligible for small measurement distances but can be recorded for root-cause analysis in hindsight.

The clear benefit of automatic compensation is that regular calibration of the equipment is no longer necessary (provided the equipment is not changed physically or electrically). In practice, a test box may be used for various loudspeakers with different jigs or baffles, in which case calibration with the golden device should be performed after each change.

It is recommended that sensors for measurement of atmospheric pressure and ambient temperature record data every 15 minutes and to an accuracy of +/-2hPa (+/-2mbar) and +/-0.5^{o}C. With this accuracy, the remaining total error following compensation of changing atmospheric pressure and temperature conditions will be within +/-0.05dB. Slightly relaxed sensor accuracies of +/-4hPa (+/-4mbar) and +/-1.0^{o}C will give a final tolerance of +/-0.1dB.

In the laboratory, compensation can be applied manually to measurements provided the atmospheric data can be measured.

Equation (19) below (from equations 6, 7 and 9) can be used to calculate the **correction** required for a measured sound pressure in the actual atmospheric conditions in both automatic and manual cases. α is the temperature coefficient of the voice coil material of the DUT and t is the actual temperature in ^{o}C of the air ***and*** acclimatised DUT, t_c was the temperature in ^{o}C at time of calibration or reference temperature in the laboratory. P is the actual atmospheric pressure and P_c was the atmospheric pressure at time of calibration or reference atmospheric pressure in the laboratory.

NOTE that the temperatures in equation (19) are in degrees Celcius for ease of use.

$$\textit{Correction in dB} = 20\log_{10}\left[\frac{P_c}{P}\right] + 20\log_{10}\left[\frac{273.15+t}{273.15+t_c}\right] + 20\log_{10}\left[1+\alpha(t-t_c)\right] \qquad (19)$$

7. CONCLUSION

The aim of the paper has been to present an area that affects everybody that performs acoustic measurements. It is hoped that the data presented will highlight the importance of giving thought and consideration to the influence of varying ambient atmospheric conditions.

Indeed, manufacturers that boast small production tolerances of the order of +/-1.0dB across running production simply cannot do so unless they take the influences described here into account. Anyone attempting to produce according to such tight limits probably suffers from poor yield and possibly cannot understand why. Furthermore, calibration at times of adverse atmospheric conditions will have a seriously detrimental effect on the outcome of produced parts – whether the manufacturer is aware of it or not.

In the laboratory, varying ambient atmospheric conditions will likely account for why the same transducer appears to have a different sensitivity across time. Variations can be significant and it is strongly advised that reference measurements, for example for documentation purposes are at least manually compensated for the influences of varying ambient atmospheric conditions.

Atmospheric pressure and particularly temperature present the largest variation and influence. Changes caused by humidity are insignificant over small measurement distances up to 20kHz.

Acclimatisation of the DUT prior to testing is essential.

It is best practice that golden devices or reference loudspeakers used in a production environment are checked by laboratory measurement at least annually. Whenever a golden device or reference loudspeaker is used to calibrate the test equipment, the data should be recorded and compared automatically to previous calibrations. In this way, you achieve traceability on the production line. The responsible technician or engineer should automatically be notified if a calibration deviates from a previous one by more than a specified limit.

The IEC 602868-1 window for climatic conditions is a reasonable recommendation in some ways although in practice the range of atmospheric pressures given is more or less meaningless. The range of temperatures is a suitable match to everyday factory conditions but the window for relative humidity is too narrow. For high-precision specifications, the atmospheric conditions (especially atmospheric pressure and temperature) must be quoted together with the data. Alternatively, loudspeaker specifications such as sensitivity should be corrected to a standard reference such as 1013hPa/20^{o}C.

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9. REFERENCES

[1] Beranek: *Acoustics*, McGraw-Hill, New York, 1954/1986.

[2] Kinsler, Frey, Coppens and Sanders: *Fundamentals of Acoustics* (4th edition), John Wiley & Sons, New York, 2000.

[3] Harris: *Absorption of Sound in Air versus Temperature and Humidity*, The University of Columbia, New York, 1966.

[4] ISO 9613-1:1993 *Acoustics - Attenuation of sound during propagation outdoors. Part 1: Calculation of the absorption of sound by the atmosphere.*

[5] Dean: *Atmospheric Effects on the Speed of Sound*, The University of Texas at El Paso, Texas, 1979

[6] Zuckerwar: *Handbook of the Speed of Sound in Real Gases*, Academic Press, 2002.

[7] IEC 60268-1:1985 *Sound System Equipment. Part 1: General*. Previously named IEC 268-1.