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Variability of room acoustic parameters with thermo-hygrometric conditions

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Abstract

The variation of the room acoustic parameters measured in an auditorium is influenced by many variables such as the equipment, the operator, the position and orientation of the sound source and the microphones, and the post-processing method used for the calculation. An influence of fundamental importance is due to the thermo-hygrometric variables, which is commonly neglected. In this article, an experimental analysis concerning the influence of the temperature, relative humidity, and air velocity on acoustic parameters is presented. Thermo-hygrometric variables have been varied and the variation of several room acoustic parameters has been analized. A statistical analysis of the correlations has been obtained and used for the evaluation of the variation of the acoustic parameters by changing the thermo-hygrometric variables. Finally, a statistical analysis has been conducted to find correlations between room acoustic parameters and thermo-hygrometric parameters.

Keywords:

Room acoustic measurements; Thermo-hygrometric measurements; Variability of room acoustic parameters; Statistical analysis

1. Introduction

The variation of acoustic parameters measured could depend on different reasons:

- characteristics of the equipment;
- skill of the operator,
- position and number of the source/receivers;
- post-processing methods;
- measurement method;
- thermo-hygrometric conditions;

This variation is commonly considered as an uncertainty in the measurement.

The determination of the uncertainty in acoustic measurements is of fundamental importance in the determination of the correct measured value. The uncertainty of a measurement could be defined as follows: "*a parameter related to the measured result, characterising the scatter of results, which can be reasonably attributed to the measured value*" [1, 2]. This assumption states that uncertainty estimation represents an approximate description of the imperfections of the experiments. In other words, uncertainty represents an error due to several aspects, which are related to the measurements itself.

The assessment of the correct experimental value in acoustics is of fundamental importance in those branches of acoustics, from building acoustics to environmental acoustics, where they are related to fixed values imposed by standards and laws.

In building acoustics, some important studies have demonstrated the importance of several factors that could influence the determination of the final value of the acoustic parameter. Öqvist [3] examined uncertainty during the measurements of impact and airborne sound insulation in industrially prefabricated Cross Laminated timbre structures. Scrosati and Scamoni [4] discussed the possibility to find a link between uncertainty on one hand, and repeatability and reproducibility on the other hand for building acoustics measurements. Mahn and Pearse [5] analyzed the evaluation of flanking transmission in structures following the EN ISO 12354-1 standard.

Other significant works in the field of uncertainty in building acoustics in the last 15 years are (chronologically) the papers by Wittstock [6], Hongisto et al [7], Kylliäinen [8], Wittstock [9], Ljunggren and Öqvist [10] and Wittstock [11]. These works analysed uncertainty in airborne and impact sound insulations, including the outcomes of relevant round robin tests.More recently, Caniato [12] analysed uncertainty in service equipment noise prediction in timber buildings. All these papers consider variables linked to specific measurement conditions and skill of the operators. One crossing paper might be the work of Caniato [13], who indirectly underlined the effects of thermohygrometric conditions during sound absorption measurements, introducing the thermal characteristics length for porous materials. One relevant article for this work was authored by Ljunggren et al [14], since it considered a link between sound insulation and measurement of reverberation time at low frequencies.

In noise control, Wszołek and Engel [2] described the estimation of uncertainty during noise measurements, focusing on microphones and sound level meter in free field conditions.

The uncertainty in room acoustics is perhaps less considered, since in this field there are fewer legal consequences when considering the experimental (measured) values and the values fixed by law. Pelorson et al in their paper of 1992 described statistically the variability of some room acoustical parameters [15]. De Vries et al [16] found a source of uncertainty for spatial parameters (i.e.: LF and IACC) in little variation of the position of microphones. More recently, San Martìn et al [17], have considered the sound source orientation as a cause of uncertainty. In other papers, Witew et al [18], [19], [20] and Knüttel et al [21] studied the effects of loudspeaker directivity in room acoustics measurements.

These works showed that directionality of the source has a significant influence on the results obtained for acoustic parameters derived from the impulse responses, especially at high frequencies. This is found to be true even for dodecahedron loudspeakers which meet the requirements of the ISO 3382 standard regarding the directional patterns of sound sources. The most sensitive parameters are C_{50}, G and IACC. Nevertheless, even within the group of reverberation times, the EDT seems to be more sensitive than the T_{30}, as the integration interval is shorter.

The influence of temperature and humidity has been considered in the field of voice alarm (VA) systems. Gomez-Agustina et al [22] as well as Yang and Moon [23] investigated their effects in the voice reproduction systems. The results showed that reverberation time increases at high frequencies when temperature and humidity increase. Consequently, speech-related parameters were seen to decrease with rising temperatures and humidity values.

Other researchers have investigated other aspects of variability in room acoustics measurements. Guski and Vorländer considered noise in measurements as an important component to be considered [24]. Tronchin et al [25], [26] found that a certain amount of variation of acoustic parameters could be found simply by elevating the microphones.

Another source of variability (uncertainty) is the numerical procedure employed for the post-processing of the measurements. The papers by Chu [27] and Hirata [28] have shown the relevance of the post-processing method chosen for the calculation of the acoustic parameters. Moreover, Lundeby et al [29] showed that the algorithms for the determination of room acoustical parameters introduce systematic differences caused by differences in time-windowing and filtering, reverse-time integration, and noise compensation.

Only a few standards analyze the influence of thermo-hygrometric conditions during acoustic (noise) measurements or propagation. This is the case of the ISO 9613-1 [30], which considers the air absorption effect in outdoor noise propagation, evaluating a direct correlation with temperature, relative humidity and static pressure.

Other standards mention the influence of temperature and relative humidity without providing a method which could assess their effects. The ISO 354 [31] standard recommends maintaining relative humidity between 30 and 90% with a temperature of 15 Celsius. Furthermore, the ISO 3740 series [32] consider the “environmental correction” during the evaluation of sound power measurements of noise sources.

2. Theoretical background and aim of the paper

The sound attenuation caused by the medium in which the acoustic waveforms propagate is normally considered for large distances, especially in outdoor propagation, and is caused by three effects: molecular relaxation, shear viscosity and thermal conductivity. Molecular relaxation represents the most consistent component of sound attenuation in the audio frequency ranges [33]. These effects increase proportionally with the square of the frequency [34]. The total absorption area A_{air} could be calculated with the following formula:

$$A_{air} = 4\,m\,V \quad (m^2) \tag{1}$$

Where *m* represents the air intensity attenuation coefficient, and *V* the volume of air in the space. Table 1 reports the values of *m* [35].

Table 1 – air intensity attenuation coefficient [35]

Relative humidity	Frequency (kHz)						
	0.5	*1*	*2*	*3*	*4*	*6*	*8*
40	0.60	1.07	2.58	5.03	8.40	17.71	30.00
50	0.63	1.08	2.28	4.20	6.84	14.26	24.29
60	0.64	1.11	2.14	3.72	5.91	12.08	20.52

70	0.64	1.15	2.08	3.45	5.32	10.62	17.91

Although it is often neglected, another important effect is the variation of the speed of sound, which is calculated with the following equation:

$$c = 331.4\sqrt{1+\frac{t}{273}} \quad (m/s) \qquad (2)$$

Where t represents the room temperature in Celsius degrees. The variation of temperature causes a variation of the speed of sound, and therefore a change in the Sabine's equation for reverberation time [22]:

$$RT = 55.3\,\frac{V}{c(A+4mV)} \quad (s) \qquad (3)$$

Therefore, the reverberation time is directly proportional to the distance and therefore to the air sound attenuation.

These effects cause a variation of sound propagation due to the variations of the medium (air), and consequently of the acoustic parameters.

For these reasons, this work reports the influence of the main environmental variables on the most important acoustic parameters normally considered in room acoustics. In particular, strength (G), clarity (C_{50} and C_{80}), definition (D_{50}), reverberation time (T_{30}), Early Decay Time (EDT), Inter Aural Cross-Correlation (IACC), Lateral Efficiency (LE) and Lateral fraction (LF) have been measured by varying temperature, relative humidity and velocity of air.

3. Experiments and methods

The measurements were performed in the University laboratory "Roberto Alessi" in Bologna, Italy, in more than 25 consecutive hours between 13.30 of 31st July and 14.45 of 1st August, with a sampling of 5 minutes, obtaining 301 set of measurements.

This day was chosen because in northern Italy and especially in Bologna the variability of temperature and relative humidity during the day/night period is considerably higher in the summer season rather than winter or other periods. Moreover, at the beginning of August, the laboratory is closed due to summer vacation and no people are attending these rooms, and the external background noise is the smallest of the entire year. For minimizing the not thermo-hygrometric variables uncertainty, the same equipment, fixed in one specific position and orientation, was employed and controlled by one operator, located in a different room. A specific MatLab script was written to perfectly synchronize in the time all the measurements.

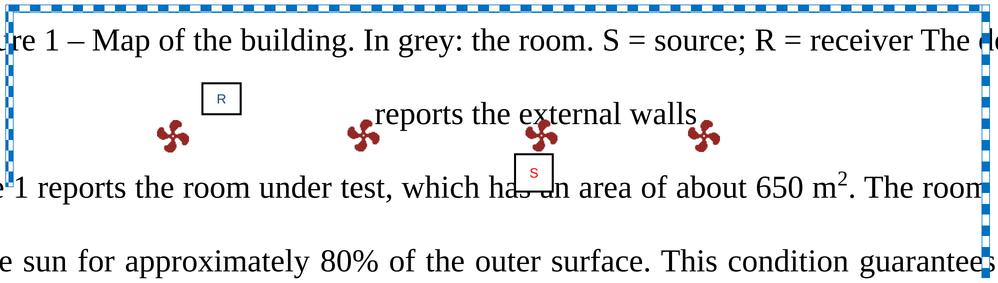


Figure 1 – Map of the building. In grey: the room. S = source; R = receiver The dotted area reports the external walls

Figure 1 reports the room under test, which has an area of about 650 m^2. The room is exposed to the sun for approximately 80% of the outer surface. This condition guarantees a relevant temperature range. The room is also provided with a variable intensity ventilation system which allows varying the velocity of the air up to a maximum of about 0.5 m/s.

3.1 Measurements of acoustic parameters

For the recordings of the measurements, of the acoustic parameters, the following equipment was employed:

- Digitally equalized dodecahedron (Look Line)
- B-format Microphone (Soundfield MK V)
- Dummy head (Neumann KU 100)

During the acoustic survey, an exponential sine sweep (chirp) ranging from 40 Hz to 20 kHz was played, and the outputs were acquired by a Motu Traveler MK3 FireWire sound card and stored as waveforms with 96 kHz sample rate and 32 bit. Figure 2 reports the scheme of the measuring method.

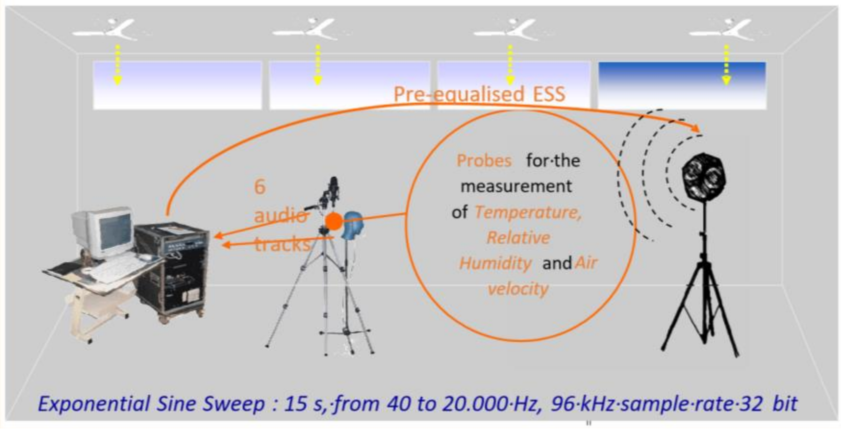


Figure 2 – scheme of the measurements

All the recordings have been post-processed deconvolving all the 1806 tracks with the corresponding inverse filter. Afterward, the acoustic parameters were then calculated using Adobe Audition software and Aurora system [36].

The B-Format microphone was employed to calculate the monoaural parameters (W channel) and the spatial parameters (LE and LF), obtained after having processed the B format impulse responses. Conversely, the dummy head allowed to measure the Binaural impulse responses (BIR), from which the IACF and IACC values have been obtained.

Moreover, both the B-Format and the binaural impulse responses were collected for further psychoacoustics tests, for evaluating the variation of the subjective perception of different musical motifs with different thermo-hygrometric conditions, which will be analysed in a further research.

3.2 Measurements of thermo-hygrometric parameters

The thermo-hygrometric parameters were measured employing two specific systems.

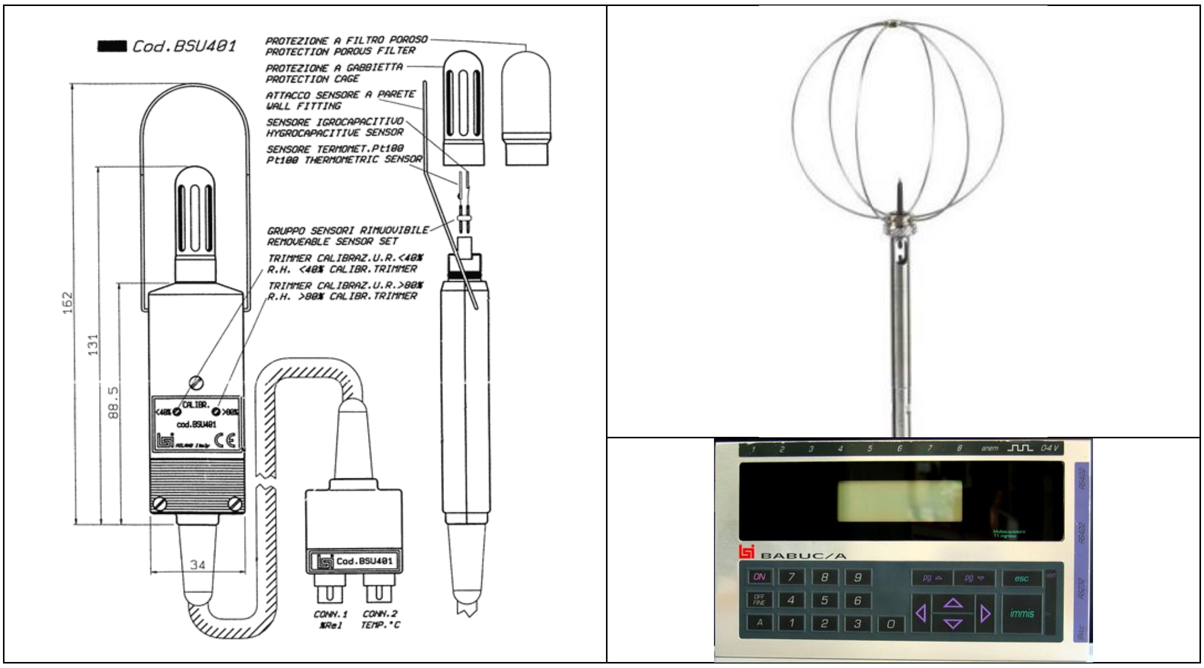


Figure 3 Hot wire anemometer and the acquiring system (BABUC, DISA)

The first (namely: "BABUC") was used for temperature and relative humidity. It has been programmed in such a way as to perform the detection of temperature and humidity at regular intervals every 5 minutes. The second (namely: “DISA”) consists of a hot wire anemometer for air velocity measurements. The mean value over a time interval of one minute was detected. Fig. 3 reports the scheme of the measuring systems.

4. Experimental analysis

Measurements at regular time intervals within a stationary system have been made, except of course concerning the thermo-hygrometric parameters. The purpose was to identify and distinguish the variations of the noise due to the physical characteristics of the medium.

The measurements of the acoustic parameters require the linearity of the system, as well as its time-invariance. These conditions are practically impossible in a normal closed space. The procedure described below is therefore intended to verify this hypothesis and attempts to quantify the variations of the acoustic parameters of an environment varying temperature, relative humidity and air velocity.

4.1 Measurement method

As mentioned above, the surveys were carried out using a pre-equalized, exponential sine sweep signal. Afterward, all the recorded tracks were post-processed by deconvolution with the inverse filter, and the acoustical parameters were calculated.

One operator, the same equipment and fixed position and orientation of the microphone and the sound source have been chosen to minimize the uncertainty of the not thermo-hygrometric variable. The measurements have been repeated for all the 25 hours, recording the wave files from the microphonic probes and the thermo-hygrometric values.

For the first 200 measurements, the ventilation system was also operated each time increasing the intensity, as regular as possible, up to the maximum and then in a similar way back until it was switched off.

Each cycle had a duration of 2 hours, from the value of v=0 up to v_{Max} and back for a total of 24 measurements. The following 100 measurements were conducted with the ventilation system switched off (v=0).

4.2 Description of the measurements

The B-Format and Binaural microphones were positioned close to each other and at a distance of about 16 meters from the dodecahedron.

The measurements were synchronized as follows:

- measurements of the acoustic parameter, stored automatically after each measurement, duration of 20 seconds (15 seconds of signal followed by 5 of no signal);

- thermo-hygrometric measurements, stored automatically during each measurement;

- anemometer measurements, stored manually, every 60 seconds.

The thermo-hygrometric data were collected delaying 10 seconds, to have the parameters of the central instant of the sound event.

The anemometer measurement was started 20 seconds before the recording of the audio signals. In this way, the average air velocity of 60 seconds was also centered concerning the sine sweep signal recording. Figure 4 reports the synchronization of all the events.

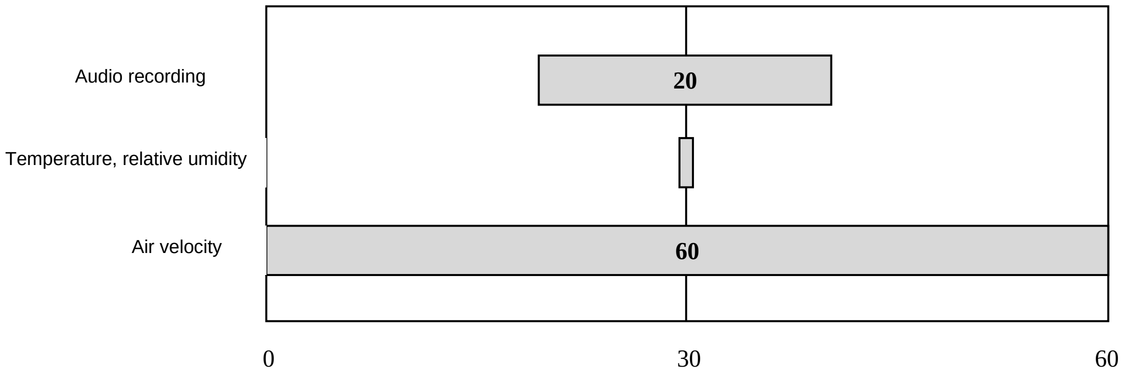


Figure 4 – Synchronization of measurements

4.3 Development of the measurements

After recording 1806 audio tracks (6 tracks for each measurement: 2 for binaural and 4 for Soundfield relating to the 301 measurements), the impulse responses have been extrapolated employing Aurora plugins. From the impulse responses, the following acoustic parameters have been calculated at the octave bands of 125, 250, 500, 1000, 2000 and 4000 Hz:

- Strength, G [dB];

- Clarity, C_{50} [dB] and C_{80} [dB];

- Definition, D_{50} [%];

- Reverberation time, T_{30} [s];

- Early-Decay Time EDT [s];

- Cross-Correlation Inter Aural, IACC;

- Lateral Efficiency, LE;

- Lateral fraction, LF.

5. Data analysis

Temperature, relative humidity and air velocity have been examined. Subsequently, a descriptive analysis of the acoustic parameters measured and of any relations between these magnitudes and the variations of temperature, relative humidity, and air velocity has been made.

5.1 Thermo-hygrometric parameters analysis

In the following, temperature, relative humidity and air velocity values are represented.

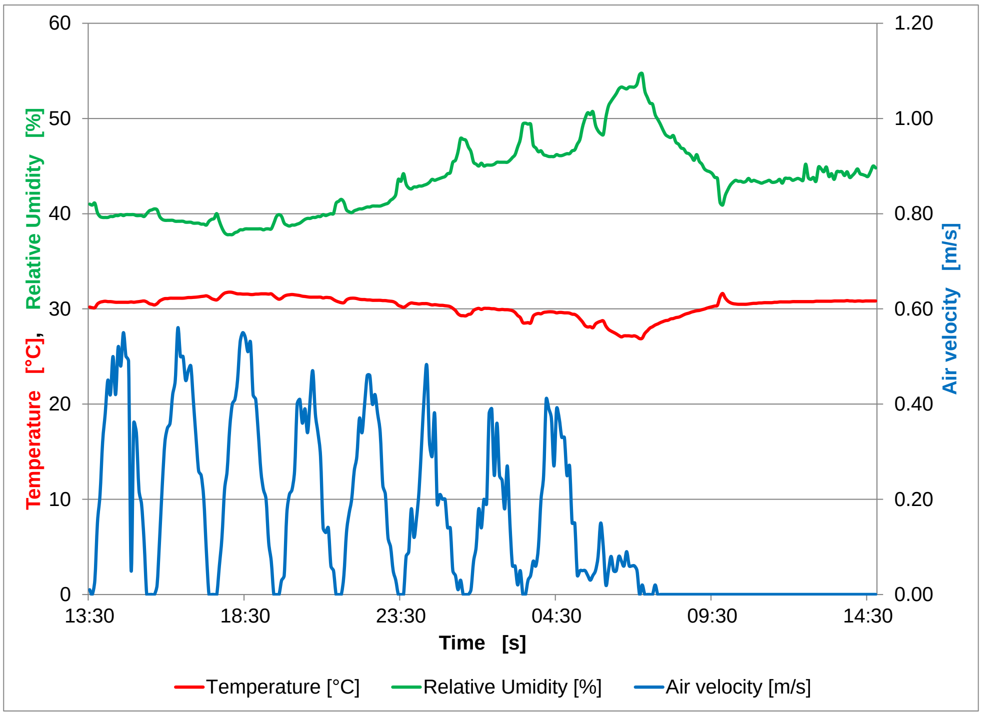


Figure 5 – Temperature, relative humidity and air velocity values

From figure 5, we could note how the decrease of temperature increases the relative humidity, and vice versa.

The measurements were carried out on 25 consecutive hours to maximize the temperature variations, which were nearly 5 °C. The variation of relative humidity was approximately 17 % and the variation of the air velocity was 0.56 m/s (Table 1).

Although these variations of air temperature and relative humidity are not enough to completely describe their link with the variation of acoustic parameters, this range represents the optimal compromise for making a 25 hours measurements during the year in an unoccupied room. In order to extend the variation, it would be useful to repeat the experiment in another period of the year, e.g. during Christmas vacation, where the laboratory is unoccupied and air temperature and relative humidity are different from summer season.

Table 1 – Descriptive analysis of the thermo-hygrometric parameters

	Temperature [°C]	Relative humidity [%]	Air velocity [m/s]
Average	30.28	43.52	0.15
Min	26.88	37.80	0.00
Max	31.77	54.70	0.56
Range	4.89	16.90	0.56

The only observed independent parameter is the velocity of the air, which has been artificially varied through the ventilation system. Temperature and relative humidity are linked by an inverse proportionality since the absolute humidity (moisture) in the air can be considered almost constant.

Furthermore, in the vicinity of the air velocity minimum, can also be present temperature minimum (and therefore greatest relative humidity).

This phenomenon is explained by the fact that being the test room rather high, and not uniform the temperature distribution, the warmer air tends to rise towards the ceiling. The action of the fans causes a mixing of the air and a higher uniformity of the temperature distribution. Conversely, if the cooling (or heating) system is switched off, there won't be any unhomogeneity in air temperature and relative humidity in the horizontal plane, and therefore at the same height we will find the same values of thermo-hygrometric parameters.

When the fans were stopped, the lower layers of air, in the vicinity of which the measuring equipments have been placed, show lower temperatures (and highest relative humidity). When the fans were in operation and carried hot air from the ceiling, higher temperatures (and therefore lower humidity) were shown.

It can be noted that the trend of the temperature and humidity is generally rather regular when the ventilation system was turned off permanently.

5.2 Acoustic parameters analysis

Some observations can be made from a preliminary qualitative analysis of the results derived from graphs below showing a pattern of parameters for different frequencies. For sake of simplicity, the following graphs report only Strength (G), Clarity (C_{50} and C_{80}) and Reverberation Time (T_{30}). The results at 1 kHz are reported in bold.

It is possible to identify three types of curves, which are reported as many significant examples:

- similar parameters trends, but with more or less markedly different amplitudes (Strength G, Soundfield W, figure 6);
- different trends, sometimes inverted, but still recognizable and similar to the curves of the parameters thermo-hygrometric (C_{50}, figure 7 and C_{80} figure 8, both from Soundfield W);
- inconsistent trends, which do not seem recognizable influences of hygrometric parameters, at least for some frequencies (Reverberation Time T_{30}, Soundfield W, figure 9).

In the latter case, a low accuracy of calculation models can explain random variations, even of a certain amount, observed in the graphs.

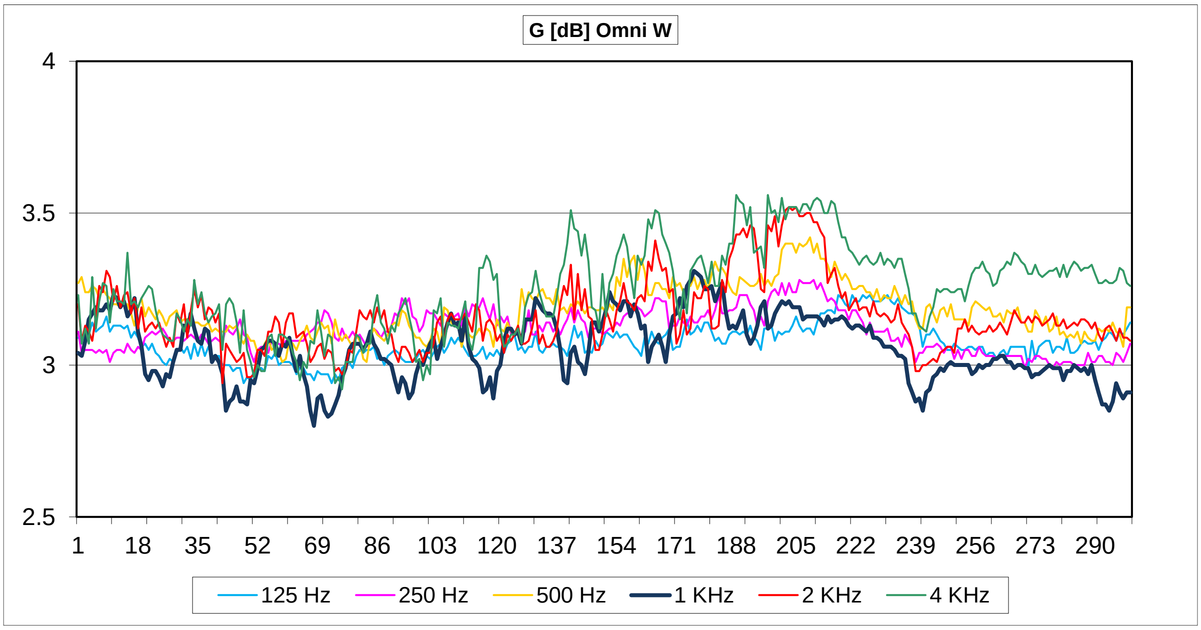


Figure 6 - G (Soundfield W) trends, similar to the various frequencies

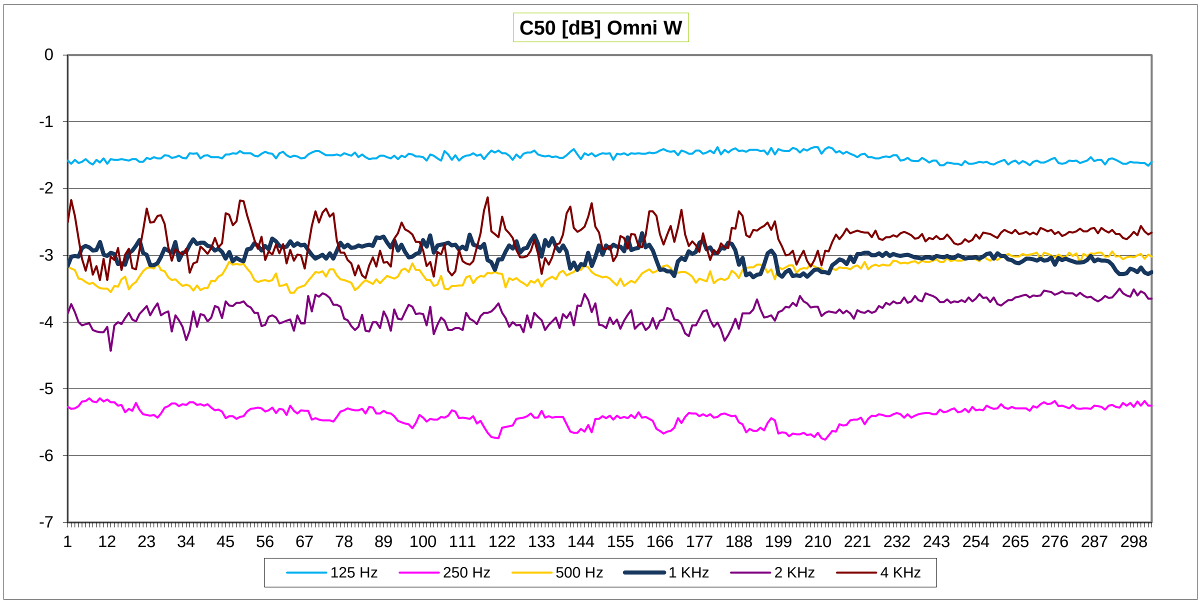


Figure 7 – C_{50} (Soundfield W) trends, sometimes different for different frequencies

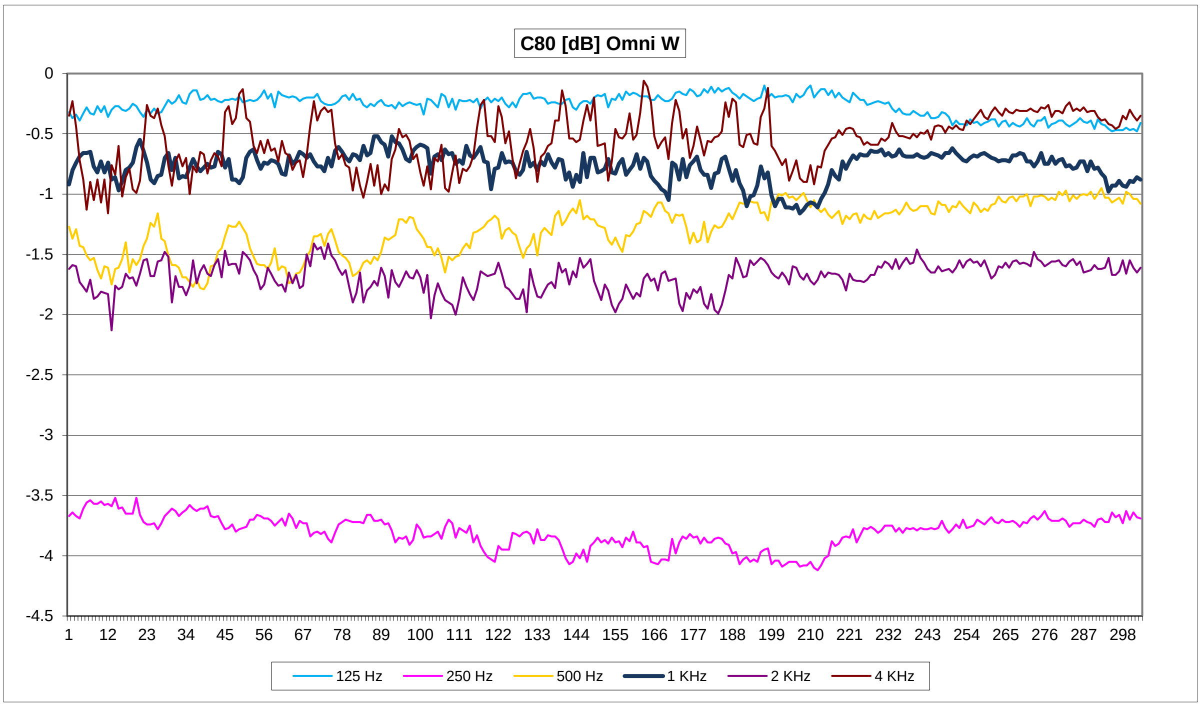


Figure 8 – C_{80} (Soundfield W) trends, similar to figure 7

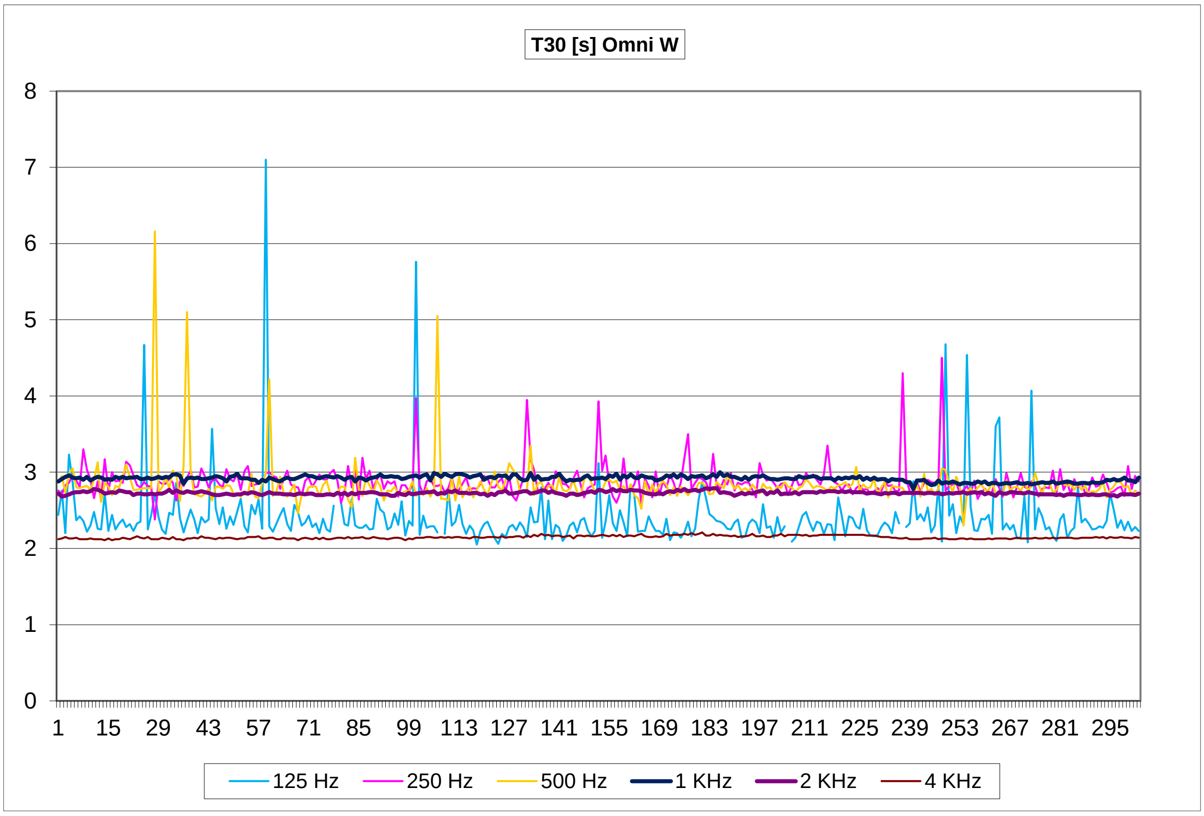


Figure 9 – T_{30} (Soundfield W) trends with very pronounced peaks

Tables below contain summary data relating to the acoustic parameters measured. Note that, for most of the parameters, both ranges of variation and the standard deviations are of a certain entity:

Table 2 - Mean value and standard deviation of the different parameters

G – Mean	3.07	3.11	3.18	3.06	3.16	3.25
G - St. dev	0.06	0.07	0.09	0.11	0.12	0.15
G - St. dev [%]	**2.0**	**2.3**	**2.8**	**3.6**	**3.8**	**4.6**
C50 - Mean	-1.52	-5.4	-3.24	-3	-3.85	-2.78
C50 - St. dev	0.07	0.14	0.16	0.15	0.18	0.24
G - St. dev [%]	**4.6**	**2.6**	**4.9**	**5.0**	**4.7**	**8.6**
C80 – Mean	-0.26	-3.8	-1.28	-0.77	-1.68	-0.55
C80 - St. dev	0.09	0.13	0.21	0.12	0.12	0.22
C80 - St. dev [%]	**34.6**	**3.4**	**16.4**	**15.6**	**7.1**	**40.0**
D50 - Mean	41.34	22	32.15	33.42	29.18	34.52
D50 - St. dev	0.37	0.54	0.78	0.74	0.86	1.27
D50 - St. dev [%]	**0.9**	**2.5**	**2.4**	**2.2**	**2.9**	**3.7**
EDT - Mean	2.24	2.47	2.87	2.83	2.57	2.06
EDT - St. dev	0.04	0.05	0.04	0.05	0.05	0.04
EDT - St. dev [%]	**1.8**	**2.0**	**1.4**	**1.8**	**1.9**	**1.9**
T30 - Mean	2.42	2.88	2.83	2.92	2.73	2.15
T30 - St. dev	0.47	0.21	0.3	0.04	0.02	0.02
T30 - St. dev [%]	**19.4**	**7.3**	**10.6**	**1.4**	**0.7**	**0.9**
IACC - Mean	0.931	0.827	0.326	0.259	0.172	0.181
IACC - St. dev	0.005	0.005	0.008	0.007	0.009	0.014
IACC - St. dev [%]	**0.5**	**0.6**	**2.5**	**2.7**	**5.2**	**7.7**
LE – Mean	0.09	0.05	0.07	0.14	0.18	0.29
LE - St. dev	0.01	0.00	0.01	0.01	0.01	0.02
LE - St. dev [%]	**5.8**	**4.0**	**6.8**	**4.3**	**3.9**	**5.9**
LF – Mean	0.13	0.06	0.08	0.17	0.21	0.36
LF - St. dev	0.01	0.00	0.01	0.01	0.01	0.02
LF - St. dev [%]	**4.8**	**1.7**	**6.0**	**4.8**	**3.8**	**4.4**

6. Statistical data analysis

A statistical analysis of the measured data, necessary to study the relationship between acoustic parameters and thermo-hygrometric parameters, has been carried out. For the statistical analysis, the SPSS software has been used.

6.1 Regression models

After having determined the variation of the acoustic and the thermo-hygrometric parameters, the next step was the analysis of the correlation between the two datasets. The first step of the study was the analysis of the parameters with a linear regression.Among the various available procedures, the "stepwise" linear regression was adopted. This procedure introduces a variable in the model at a time and discards variables redundant or less effective concerning those already inserted or those worsening of the model. In this way, only improved variables are introduced. Nevertheless, the linear regression test was performed and didn't give enough good results.

6.2 Improvement of the model

Since the linear regression analysis had led to results which, although promising, were lower than expected, it has been tried to improve the model by assuming that the functions between the variables were not only linear.

For this purpose, a small sample was analyzed in detail before proceeding to an analysis of all the acoustic parameters.

Data sets, for which the previous linear regression analysis was calculated from the various models with different R^2, have been selected. For each selected data and each independent variable (temperature, relative humidity and air velocity) taken individually, R^2 has been calculated with a "Curve Estimation" procedure. Although this calculation procedure does not permit to insert more independent variables, it allows to compare regression models applied to the same data set. Comparing the R^2 of the different models, it has been found the best fitting one.

Figure 10 reports an example of the output of the *Curve Estimation* procedure performed on the data set G (Soundfield W) at 500 Hz, considering the temperature as the independent variable.

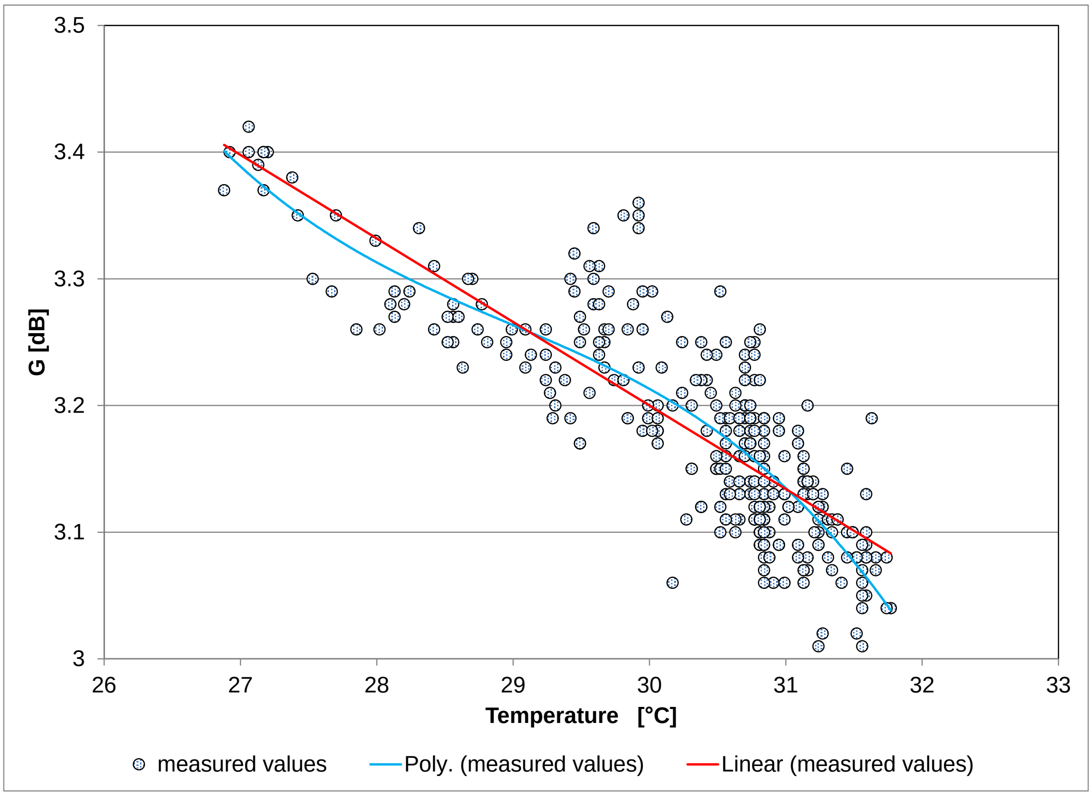


Figure 10 – Regressions between acoustic parameter (G Soundfield W at 500 Hz) and temperature

From figure 10, which shows the correlation between temperature and the acoustic parameter, it has been seen how the cubic models fit much better than the linear model.

An analysis of all the data sets of the sample showed that the cubic model presents an improved R^2.

6.3 Refinement of the model

The results obtained are referred to the independent variables taken one at a time, however it can be considered that the results are also extensible to a combination of them. Since the linear regression with multiple independent variables starts from an assessment of the correlations between the dependent variable and the individual parameters and having found their improvement, it can be assumed that also the final model will be better.

Furthermore, another improvement consisted in considering the square and the cubic values of the of independent variables (i.e. temperature, relative humidity and air velocity). It was possible to model the expected value of the acoustic parameters as an n^{th} degree polynomial, yielding the general polynomial regression model, in which n is equal to 3.

.

The final result is a model, more complex, but more accurate, as reported in equation 5:

$$y = A + B_1 t + B_2 t^2 + B_3 t^3 + C_1 u + C_2 u^2 + C_3 u^3 + D_1 v + D_2 v^2 + D_3 v^3 \quad (5)$$

The previous polynomial model leads to a considerable reduction of the difference from the measured values, as seen in figure 10.

The presence of square and cubic values of the variables, however, means that very small values (e.g. reverberation time, expressed in seconds) are compared with very large values (e.g., air temperature, expressed in Celsius degrees). This could cause having coefficients too small with consequent worsening of the model due to problems of calculation.

To solve this discrepancy, a normalization of the three independent variables has been made. After having considered different hypothesis, which includes the difference between the recorded value and the minimum value, a solution was here used: the variables have been replaced with the difference between recorded value and average value. This helped to obtain lower values, thus more easily comparable with the acoustic parameters. R2 obtained from cubic and linear regression models.

The R^2 obtained, starting from three different versions of the same independent variables, have been compared. The comparison was made on a limited sample (5 parameter groups, each consisting of six octave-bands); the best R^2, using the differences from the mean value of the initial variables, as independent variables, have been obtained.

Figure 11 shows the comparison of the R^2 of the models (one of five groups of parameters of the sample) calculated with the different methods.

The first model is the one obtained by linear regression while the other three are obtained from the improved regressions from squared and cubic variables (from the original values of thermo-hygrometric parameters, from the differences related to the average values and from the differences related to the minimum values respectively).

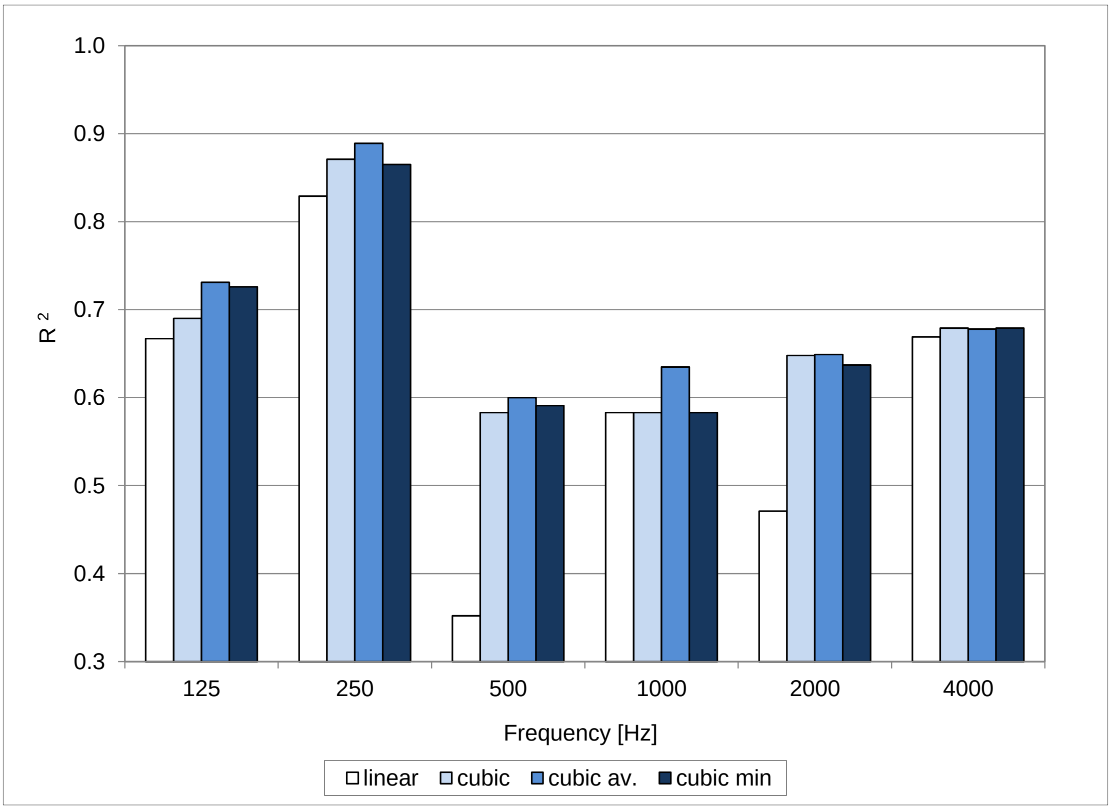


Figure 11 - Regressions comparison example

From the results of the comparisons made on the sample, cubic regressions using as independent variables Δt, Δu and Δv, calculated as differences from their average values

($\Delta t = t - t_{av}$, $\Delta u = u - u_{av}$, $\Delta v = v - v_{av}$), has been calculated:

$$y = A + B_1(\Delta t) + B_2(\Delta t)^2 + B_3(\Delta t)^3 + C_1(\Delta u) + C_2(\Delta u)^2 + C_3(\Delta u)^3 + D_1(\Delta v) + D_2(\Delta v)^2 + D_3(\Delta v)^3 \quad (6)$$

Table 3 shows improvements of the R^2 obtained with cubic and linear regression models. For C_{50}, C_{80} and D_{50}, the average of R^2 always greater than 0.640 has been obtained, for G a value greater than 0.726 has been obtained. The average of R^2 for the EDT is 0.665. Only the averages of the R^2 of T_{30}, IACC, the LE and LF are under 0.5.

The average improvement of the R^2 of all models is 0.11 (R^2=0.55 for the cubic regression, compared to R^2=0.44 for linear regression).

Table 3 - Improvements of the R^2 from linear regression and improved cubic regression.

R^2_G	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**	**Average Lin**	**Average cubic**
G lin	0.399	0.569	0.723	0.744	0.724	0.750	0.652	
G cubic	0.578	0.615	0.767	0.826	0.756	0.814		0.726
C_{50} lin	0.392	0.513	0.781	0.502	0.558	0.483	0.538	
C_{50} cubic	0.535	0.598	0.844	0.636	0.712	0.596		0.654
C_{80} lin	0.506	0.564	0.894	0.409	0.443	0.497	0.552	
C_{80} cubic	0.664	0.635	0.900	0.497	0.561	0.581		0.640
D_{50} lin	0.392	0.510	0.781	0.504	0.559	0.481	0.538	
D_{50} cubic	0.532	0.597	0.844	0.639	0.714	0.595		0.654
EDT lin	0.712	0.494	0.450	0.734	0.467	0.125	0.497	
EDT cubic	0.796	0.708	0.561	0.734	0.685	0.504		0.665
T_{30} lin	0.024	0.000	0.022	0.259	0.320	0.538	0.194	
T30 cubic	0.024	0.000	0.040	0.446	0.458	0.649		0.270
IACC lin	0.353	0.582	0.190	0.146	0.283	0.361	0.319	
IACC cubic	0.481	0.691	0.411	0.234	0.341	0.523		0.447
LE lin	0.576	0.000	0.599	0.210	0.297	0.476	0.360	
LE cubic	0.702	0.000	0.616	0.405	0.333	0.602		0.443
LF lin	0.419	0.000	0.545	0.415	0.257	0.310	0.324	
LF cubic	0.548	0.000	0.557	0.574	0.334	0.531		0.424

Figure 12 reports the measured values, the values estimated by linear regression and the values estimated by improved and refined regression (namely, “cubic”).

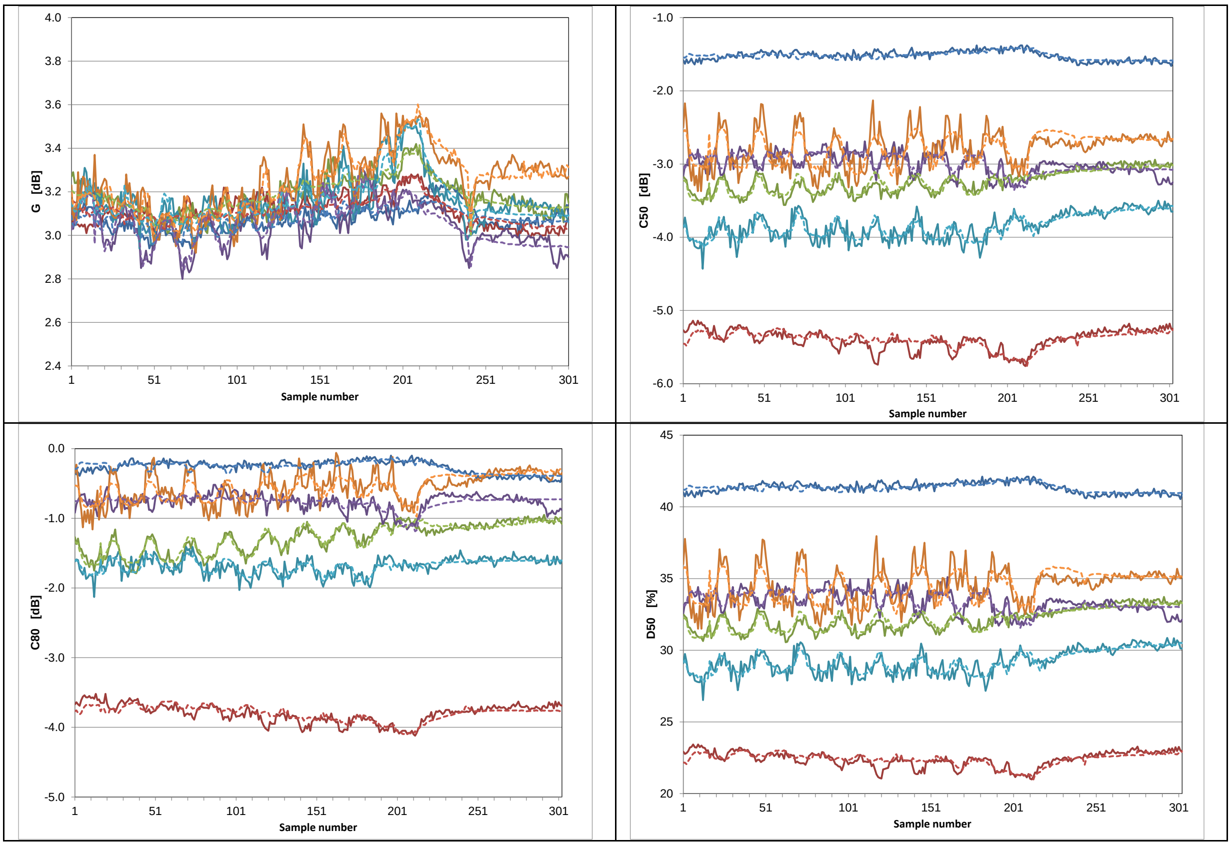
It may be noted that the "cubic" regression fits much better than the linear one.

6.4 Analysis with the variation of the acoustic parameters

The cubic correlation reported in equation 7 considers the acoustic parameter variation, Δy, respect the thermo-hygrometric parameters variation Δt, Δu, Δv:

$$\Delta y = B_1(\Delta t) + B_2(\Delta t)^2 + B_3(\Delta t)^3 + C_1(\Delta u) + C_2(\Delta u)^2 + C_3(\Delta u)^3 + D_1(\Delta v) + D_2(\Delta v)^2 + D_3(\Delta v)^3 \quad (7)$$

The following figure 12 reports the comparisons between measured and predicted one octave band acoustic parameters here considered, from 125 Hz to 4 kHz.



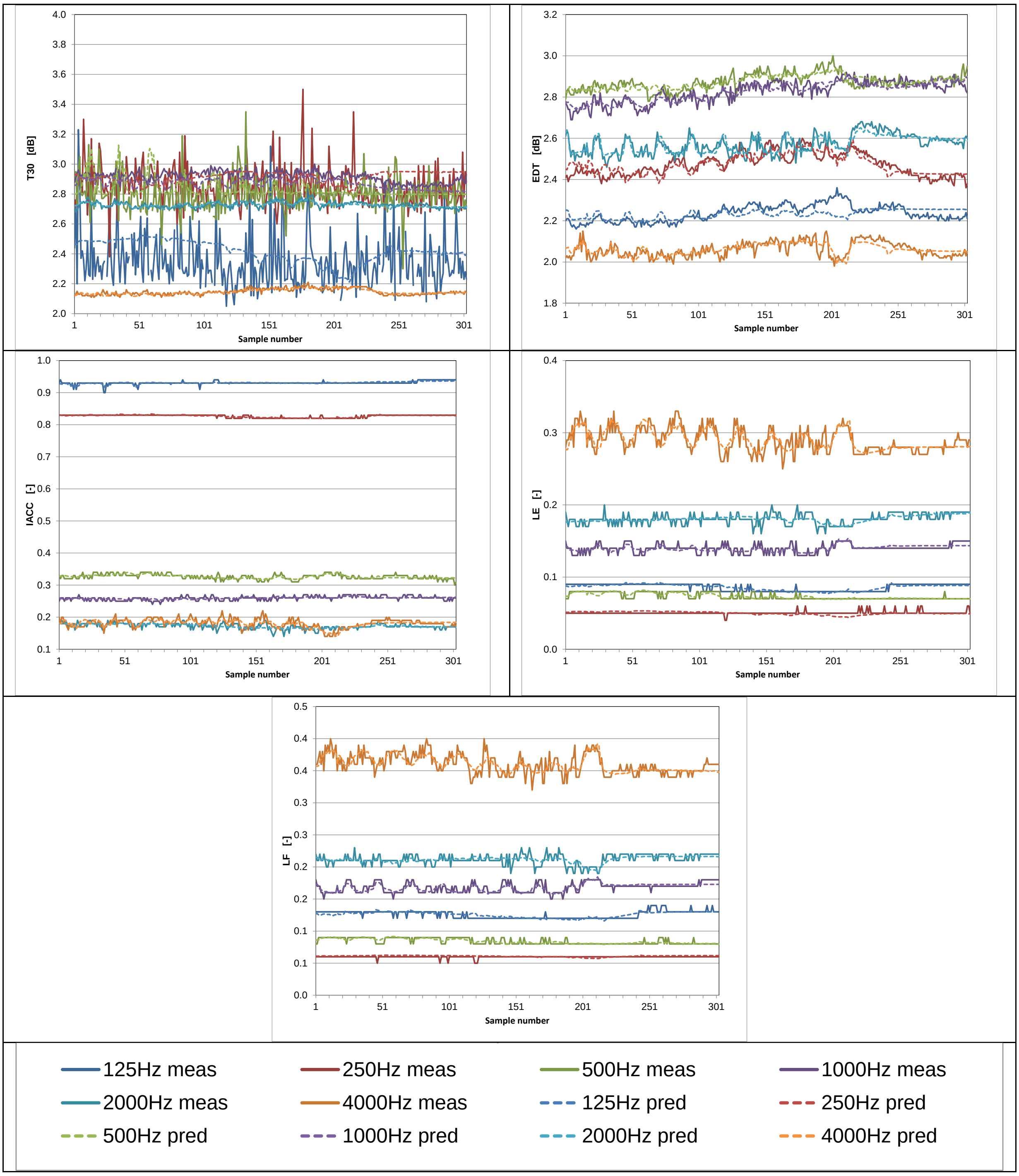


Figure 12 – Measured and predicted delta acoustic parameter from 125 Hz to 4 kHz. For T_{30}, the most evident peaks found in the measurements (see figure 9) have been removed,

The following tables (from 4 to 12) report the regression coefficients in one third octave band (125-4000 Hz).

Table 4 – Regression coefficient for G.

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
B1	-0.084	0.046	0.155	0.037	0.033	0.101
B2	0	0	0	0	0	0
B3	0.012	0	0	0.008	-0.016	0
C1	-0.007	-0.011	0.061	0	0	0.043
C2	0.003	0	0	0	0.003	0
C3		0	0	0	-0.001	0
D1	0.340	0	-0.894	0	-0.820	-1.025
D2	-1.772	3.100	0	-0.593	0	0
D3	2.279	-5.898	2.273	0	3.023	4.071

Table 5 – Regression coefficient for C_{50}

	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
B1	-0.041	0.182	0.111	0	0.191	-0.071
B2		-0.112	0.039	0	0	-0.070
B3	0.007	-0.043	0	0.028	-0.052	0
C1		0.040	0.026	-0.011	0.041	0
C2	0.002	0.007	-0.003	0	0	0.008
C3		-0.001	0	0.001	-0.001	-0.001
D1	0.133	0	-0.910	0.717	-0.900	-1.460
D2	-1.354	2.290	1.681	-1.874	4.281	0
D3	2.315	-3.785	0	0	-7.653	4.246

Table 6 – Regression coefficient for C_{80}

	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
B1	-0.084	0.046	0.155	0.037	0.033	0.101
B2	0	0	0	0	0	0
B3	0.012	0	0	0.008	-0.016	0
C1	-0.007	-0.011	0.061	0	0	0.043
C2	0.003	0	0	0	0.003	0
C3	0	0	0	0	-0.001	0
D1	0.340	0	-0.894	0	-0.820	-1.025
D2	-1.772	3.100	0	-0.593	0	0
D3	2.279	-5.898	2.273	0	3.023	4.071

Table 7 – Regression coefficient for D_{50}

	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
B1	-0.225	0.732	0.565	0	0.912	-0.368
B2	0	-0.449	0.197	0	0	-0.375
B3	0.038	-0.172	0	0.147	-0.245	0
C1	0	0.162	0.134	-0.055	0.195	0
C2	0.012	0.028	-0.016	0	0	0.042
C3	0	-0.004	0	0.004	-0.006	-0.004
D1	0.739	0	-4.573	3.688	-4.278	-7.606
D2	-7.552	9.274	8.484	-9.632	20.456	0
D3	13.029	-15.406	0	0	-36.407	22.298

Table 8 – Regression coefficient for EDT

	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
B1	-0.006	-0.046	0.025	0.051	-0.049	-0.033
B2	0.005	0	0	0	0.031	0
B3	0	0.017	-0.006	0	0.006	0.008
C1	0	0	0.017	0.021	-0.010	0
C2	-0.001	0	0	0	-0.002	-0.001
C3	0	0	0	0	0	0
D1	-0.116	0.281	0	-0.076	-0.261	0
D2	0.244	-0.803	-0.977	0	1.329	0
D3	-0.006	0	2.341	0	-1.741	0.944

Table 9 – Regression coefficient for T_{30}

	125 [Hz]	250 [Hz] bin L	500 [Hz]	1000 [Hz] bin L	2000 [Hz]	4000 [Hz]
B1	0	0	0	-0.033	-0.012	0
B2	0	0	0	0	-0.007	0
B3	0	-0.006	0	0.001	0	0.002
C1	-0.018	0	0	-0.005	0	0.006
C2	0	-0.003	0	0	0	0
C3	0	0	0	0	0	0
D1	0	0	0	0.244	0.116	0.076
D2	0	0	0	-0.684	0	-0.240
D3	0	0	4.437	0	-0.604	0

Table 10 – Regression coefficient for IACC

	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]

B1	0.006	0.002	0	0	-0.003	0.006
B2	0	0	0	0	0	-0.002
B3	-0.001	0	0	0	0	0
C1	0.002	-0.001	-0.001	0.001	-0.003	0
C2	0	0	0	0	0	0
C3	0	0	0	0	0	0
D1	0.005	-0.015	-0.013	-0.011	0	0.023
D2	0.088	0.045	0	0.061	0.134	-0.224
D3	-0.446	0	0	0	-0.447	0

Table 11 – Regression coefficient for LE

	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
B1	0.004	0	0	0.002	0.008	0.006
B2	0	0	-0.002	0	0	0
B3	0	0	0	-0.001	0	-0.002
C1	-0.001	-0.001	-0.001	0	0.002	0
C2	0	0	0	0	0	0
C3	0	0	0	0	0	0
D1	-0.012	0.001	0.010	-0.020	0	0.066
D2	0.035	0	0	0.120	0	0
D3	0	0	0	-0.249	0	0

Table 12 – Regression coefficient for LF

	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
B1	0.005	0.001	-0.002	0.002	0	0
B2	0	0	0	0	0	0
B3	-0.001	0	0	-0.001	0	-0.002
C1	0	0	-0.001	0	0	-0.002
C2	0	0	0	0	0	0
C3	0	0	0	0	0	0
D1	-0.013	-0.001	0.008	-0.037	0	0.042
D2	0.125	0	0	0.130	0.119	0
D3	-0.254	0	0	-0.208	-0.344	0

The limits of validity of the formula 7 are those related to the measuring range of the measurements (Table 1).

It was not possible to evaluate the influence of temperature or relative humidity only, since these variables are closely linked (with decreasing temperature the relative humidity should decrease with a real-time control).

7. Discussion

The analysis of the data should consider separately the statistical analysis of the measurements from the statistical models for each parameter.

Considering the results from the acoustic survey, the following points are particularly relevant.

1) The first part of the measurements (from 1 to 200 measures) gathered acoustical parameters that were strongly influenced by the air velocity. The graphs, as well as the tables, highlight this strong link. When the air conditioning system was switched off (imposing no air velocity), the variation of the acoustical parameters changed significantly: In other words, the variation of air velocity in the room represents the most relevant environmental parameters for the variation of the acoustical parameters.
2) Some acoustic parameters demonstrated a strong influence not only with air velocity but also on temperature and relative humidity (e.g.: Strength; Clarity C_{50} and C_{80}, T_{30}). It should be noted that in case of high different distribution of air temperature in a room (for example caused by a not properly designed heating system), the temperature gradient might cause convective air flows from different seat positions, provoking both an important variation of acoustic parameters (i.e. of the sound perception), and a variation on the tuning of musical instruments. This effect is particularly relevant for those instruments (like brasses, organ pipes, wind instruments), where the sound generation is directly caused by the airflow in between them, The temperature differences might cause thermal dilatations of the metals, and therefore an out-of-tuning of the musical instruments.

3) The link between thermo-hygrometric conditions and acoustic parameters vary considerably with frequency. Figure from 6 to 9 reports the variation of Strength, Clarity (50 and 80 ms) and T_{30}, in which it could be noted that Strength and Clarity are less influenced by changes in air velocity at low frequencies, whilst, the link is more evident at mid-high frequencies. On the other hand, Reverberation time varies considerably at low frequencies, whilst at mid-high frequencies, it resulted much more stable.

Considering the statistical models obtained after the development of the cubic regression models, it could be noted that:

a) As per the experimental statistical analysis, the difference between the two configurations (air velocity system switched on or off) is remarkable. The models here proposed consider both the configurations (air velocity on and/or off). Nevertheless, in a further step, it might be useful to develop new models which consider only variations in temperature and relative humidity, assuming that in an enclosed room (like an auditorium, a theatre, or a concert hall) the air velocity might be set to zero. This means that further statistical analysis could be carried out from these data separating the two different groups.

b) The cubic models here proposed gathered very good results even in case of variation of air velocity and temperature/relative humidity. However, in the last case, it should be noted that the surveys were conducted in the summer season, i.e. at a relatively high temperature (from 25 to 32 Celsius degrees) and high humidity conditions. It might be possible to refine the models considering different thermo-hygrometrical conditions, i.e. during winter season, artificially varying temperature and humidity. This might help to find another important set of coefficients which could better describe the links in more frequent environmental conditions

c) Some acoustical parameters (i.e. Reverberation Times like T_{30} and EDT) showed at low frequencies an important incoherent variation which does not depend considerably on the thermo-hygrometric conditions, but rather from other aspects. This was not found at mid-hight frequencies, where the Reverberation Times (T_{30}, EDT but also others) resulted much more stable, and a link with thermo-hygrometrical variations was much easier found

8. Conclusions

In this work, the influence of the main environmental variables on the most important acoustic parameters has been analyzed. In particular, Strength (G), Clarity (C_{50} and C_{80}), Definition (D_{50}), Reverberation Time (T_{30}), Early Decay Time (EDT), Inter Aural Cross-Correlation (IACC), Lateral Efficiency (LE) and Lateral fraction (LF) have been measured by varying temperature, relative humidity and air velocity.

The experimental analysis and subsequent statistical analysis have led to the definition of the regression coefficients used to obtain indications regarding the variability of the acoustic parameters to vary the thermo-hygrometric conditions.

The acoustic parameters most influenced by variability of thermo-hygrometric variables were C_{80} and T_{30} while the least influenced were D_{50} and EDT.

It was also found that air velocity strongly influenced the calculation of almost all the acoustical parameters. This was more evident at low frequencies for all the reverberation times (T_{30} and EDT) and at mid-high frequencies for energy parameters (Clarity, Definition).

The statistical model here proposed is based on the cubic regression model, which better fit the experimental data. Since the variation of acoustical parameters due to air velocity was predominant, a further study will focus only on the variation due to temperature and relative humidity parameters, assuming that in an auditorium the air velocity would be set to zero, Moreover, a further study will focus on a different range of temperature (from 18 to 25

Celsius degrees) to check whether the regression coefficients here proposed could still be used also in different conditions

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