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Infrasound and low-frequency noise immission. Structural vibrations induced by industrial noise. Improving the ISO 1996-2:2017 in order to propose a plausible standardized procedure for using in Legal noise assessment

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ABSTRACT

It is well known that dBA measurements don't are the best tool to evaluate an alleged noise/vibration disturbance, mainly when impacted dwellings are in a mixed acoustical zones. The results of the measurements, made in Peru inside and outside dwellings subjected to structural vibrations, are presented here. The issue is that there is not always a simple way to distinguish a specific sound from the total sound, and methods recommended in the ISO 1996-2 Standard are very general. An empirical criterion had to be created to find the level of specific sound contained within the total sound. These acoustic determinations consist of removing the outlier values from a time-history filtering of the total sound. In this work, the author proposes a new method of employing statistical tools, adapting Pearson's criterion, using discrete mathematics, inference, and acoustics criteria in order to develop a computer program to remove spurious noise with not complex algorithms. The purpose of this Paper is to share to the acoustician community that it is plausible to achieve a standardized method, in the sense that an algorithm could be agreed among specialists for having an "universal computer program" to determine the specific sound contained in the total sound.

Keywords: Low frequency, Noise descriptor, Sound, Standardization.

1. INTRODUCTION

It exists a plenty publication concerning about that dBA measurements under estimate the low-frequency contents and infrasound levels, also. Both the WHO and the I-INCE (1, 2) warn about the problems of using the dBA as a single descriptor to measure infrasound and low-frequency noise (ILFN). So, it is well known among acousticians that global dBA measurements are insufficient to assess a noise problem, but the worldwide legislation is based on this descriptor. The problem is when a technician or untrained persons with no proper training into ILFN acoustics problem, they could arrive at mistaken conclusions by using dBA solely.

It has been observed in most of the Legal Noise Protocols around the world that the common practice is using just dBA measurements, and sometimes the impact on ILFN it is a separate concept, like it if were a different issue. Only a few countries have a specific and logic way to analyze the low-frequency content in their Legislation. This Paper covers not only this problem but how to discriminate the specific sound from a *total sound* registered by a SLM, because the ISO 1996-2:2017 gives indication or some ways to do that, here the Authors present one plausible solution.

This work presents the results carried out in a population 2,600 meters above sea level in the Andean Mountains in Peru, because it is the only source of noise/vibration in the area: a sewage treatment to 250 m from the house.

2. Objectives and geographical characteristics and Instrumentation

The most important goal was to determine the alleged noise/vibration disturbance of the sewage pumping plant. The monitoring work started in May 2016 and is still ongoing. The other is to know the sound landscape existing in the population with no plant noise; i.e., the condition of the environmental

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noise /vibration baseline, and the infrasound and low-frequency noise (ILFN) levels. This action should manage auditory skills (Forensics Science), where low-frequency noise is a health problem.

2.1 Physical geography and weather report

Considering the mountains area where the work was done, it is a semi desert environment, according to Köppen, classification is a subtype: Tropical and subtropical desert climate (Bwk code); a subtropical anticyclon, or subtropical high, inhibits precipitation (because of descending air, elevated inversions, and clear skies), and wind velocity (See Fig. 1-b) always is below 2 m/s only during a few daylight hours (wind absence on night).

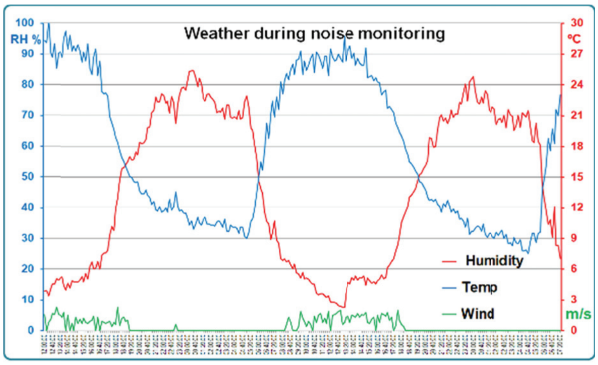

Figure 1 – (a) View of the population from the plant (b) 48 hour's weather data

It should be noted in Fig. 1-a that the houses are at a higher altitude than pump station, and the measurements were conducted inside a house near to an underground pipeline which transports mining affluent to a sewage treatment plant that is 250 m distant from the house.

2.2 Acoustical instrumentation

It is a good practice to measure both places simultaneously: at the receiver point and near the noise emitter (pumps building), so the following instrumentation was used:

a. Indoor: Sound level meter analyzers with one-third-octave band (10 Hz to 20 kHz), CESVA® instruments, a class 1 SC420® model. Dry battery.

b. Outdoor: Sound level meter analyzers with one-third-octave band (6.8 Hz to 20 kHz), BSWA® instruments, a class 1 308® model. Dry battery and solar panel.

c. Vibrometer, CESVA® instruments, a class 1 VC431® model, 500 mV/g triaxial accelerometer AC032® model. Dry batteries and solar panels.

d. A class 1 sound calibrator, AIHUA® AWA6223F Multifrequency model.

e. Weather meter, a KESTREL® 4500NV. Two digital audio recorders, ZOOM® H1.

3. INTRODUCING FORENSIC SCIENCE INTO ACOUSTICS MEASUREMENTS

This Paper presents the results of one ILFN assessment by means of Forensic tools applied to environmental acoustic measurements. The reason for this method was because it was not clear whether the noise inside the dwellings was airborne or from the ground; also, there was less certainty if the acoustic emission was from the industrial facility under study. The work was carried out near a sewage treatment plant to 250 m away from the house, which is to 20 m from a buried pipeline (inside which flows down the affluent liquids and water from the mine).

It should be considered that Acoustics for noise measurements is a new branch of Forensic Sciences, and legal noise assessment is intended under Audit activity. Therefore, it is important to get a custody chain to keep the noise data safe, simultaneously using more than one SLM as a way to correlate a sound emission from a specific sound emitter.

The assessment was requested by the Authorities, so it was mandatory to use just dBA measurements. However, in order to do a Forensic Acoustics audit, ISO standards needed to be used for the noise/vibration assessments in order to rule out the alleged annoyance. In order to avoid any future complaints, the study was conducted during continuous 48 hours as follow:

Table 1 – Intervals time where the plant was on duty and off duty

Plant on duty	Plant off duty	Plant on duty
day #1: 9 am - day #2: 5 am	day #2: 5 am to 7 pm	day #2: 7 pm – day #3: 9 am

4. RESULTS OF 48-HOUR MONITORING NOISE/VIBRATION LEVELS

Since the assessment was requested by the Authorities, it was mandatory to use just dBA measurements, but this work enhanced the legal requirements because the most important thing was to determinate the ILFN immision under low levels of environmental noise; Fig 2 shows the outdoor (a) and the indoor (b) situation.

Figure 2 – (a) Outdoor monitoring station (b) Indoor monitoring station

The outdoor station it was just above the buried pipeline front the house across the street.

4.1 Time-history of the noise and vibration levels versus affluent flow

The reason why it is important to considerer Forensic Acoustics, so enhancing the acoustics study on IFLN, others noise descriptors or vibration data will be imperative. Fig. 3 shows, per each second, the time-history of (a) indoor noise and (b) indoor vibration level: on right axis both correlated with affluent flow on left axis. The vibration total value of weighted W_m (WBB) rms acceleration is obtained according (3), but it was used dB values referenced to 1 $\mu m/s^2$.

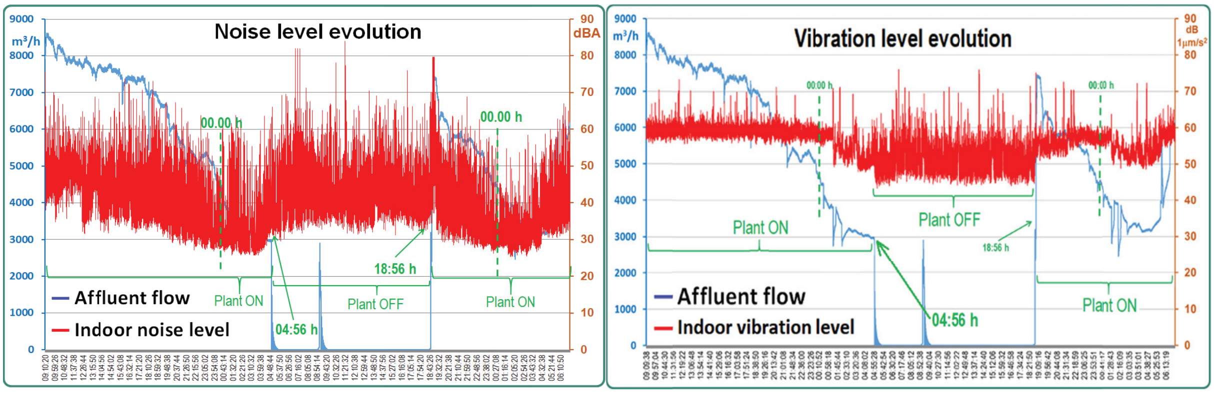

Figure 3 – (a) Noise levels time-history (b) Vibration levels time-history

Fig. 3-b shows that vibration immission has a strong dependence on mechanical energy emitted from the buried pipeline, but it is not the same with noise level immission: although the sound level fluctuates with the affluent flow (Fig. 3-a), when the plant is off duty the sound level increases, because of the urban noise.

4.2 Not information of ILFN levels by using dBA. ILFN immission from the buried pipeline

Because of the stakeholder's claim of indoor hum annoyance and rattling windows, one-third band spectrum in two ranges was used: (i) Infrasound range from 10 Hz to 20 Hz (limited by the SLM used); (ii) low-frequency range from 16 Hz to 200 Hz according to (4). There is no audible pump noise outside the houses, because the plant is more than 250 m away to the affected house, for this reason, a specific ILFN analysis had been conducted during night hours in order to discard daily urban noise.

Fig. 4-a displays, per each second, a zoom during night hours when the plant was turned off, where it is interesting to see how the sound level in dBA increases. Fig. 4-b shows, per each second, the time-history of @25 Hz level evolution; both graphics present on right axis the sound level, which is correlated with affluent flow (on left axis).

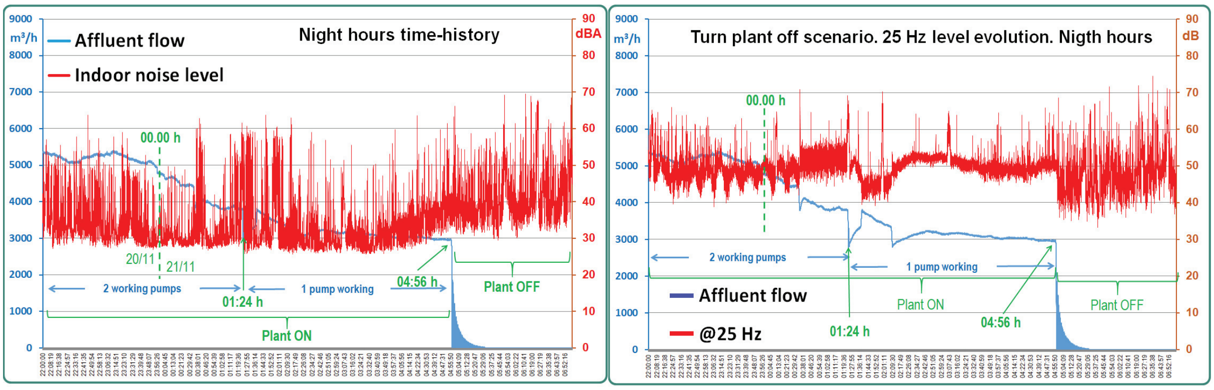

Figure 4 – (a) Indoor dBA noise level - (b) Indoor low-frequency @25 Hz level (re dB 20 µPa)

In Fig. 4-b, the 25 Hz sound level has strong dependence on the acoustic energy radiated from the house's walls, meaning a structural vibration induced by the groundborne mechanical energy from buried pipeline; when the plant is OFF, the 25 Hz sound level freely oscillates, showing a big variance among maximum and minimum because of vehicle pass-by vibrations.

5. HOW TO ESTIMATE THE *SPECIFIC SOUND* LEVEL USING DISCRETE MATHEMATICS

The author have been presented a mathematical reasoning (5) in order to simply exclude the unwanted sound from the total sound file by means of discrete mathematics.

5.1 A new idea of "basal noise" applied to environmental noise measurement

It is common to find the "basal noise" concept in medical jargon, but it is possible to use it in environmental noise measurements. According to Cambridge on-line dictionary, basal shall be understand as "*forming the bottom layer of something*".

For years the statistical L_{A90} (or L_{A95}) level has been used as a notion of *background noise*, or more recently, representative of the *residual sound* value, true only when the emitter is off, and the issue is how to estimate the *specific sound* which is in the total sound, so a priori, it seems impossible to do it.

Actually, the *specific sound* level and others noise levels are part of the *total sound*, so the noise from other sources not interested are "mounted" onto the *specific sound*, because they overlap; then it is possible to do an empirical statement: Beneath a statistical value, all sound levels are part of the specific sound and other noises impossible to identify, such as faraway noise sources and natural ones (birds, pets, weather, etc.).

The *environmental basal noise* concept appears to be useful for the empirical model presented in this Paper, it means that the *specific sound* should be appraised by a statistical value, for instance, all the sound levels below these reference percentile level belong to *environmental basal noise* (where the specific sound is included), on the contrary they will be consider as outliers.

5.2 The ISO series 1996: Measurement and assessment of environmental noise

For years, acousticians have pondered how to eliminate *unwanted sound*, which is the sound which doesn't belong to the noise source of interest. Some of the most common practices have been:

- **a.** To conduct measurements on holidays, because of low levels of urban noise.
- **b.** To turn on/off sound sources, though this is impossible to do on industrial sites or with machines under mandatory continuous work orders.

The ISO 1996 3rd Edition was established with a group of informative instructions, one of which has been resolved by the author previously (6, 7): "*Record the time history of the noise to be measured and use statistical or other methods to exclude unwanted sound.*" (4).

5.3 Expanding the scope of ISO sound designation to a Venn diagram

ISO 1996-1 (4) presents an important concept to understand the acoustics complexity of the total sound, in the sense of showing its intrinsic components, but the easy way to find out one possible solution is transforming the ISO sound designation into a manageable mathematical algorithm; the first immediate inferences of their categorical proposition is making a conversion to a Venn diagram, Fig. 5 shows the assumed obversion.

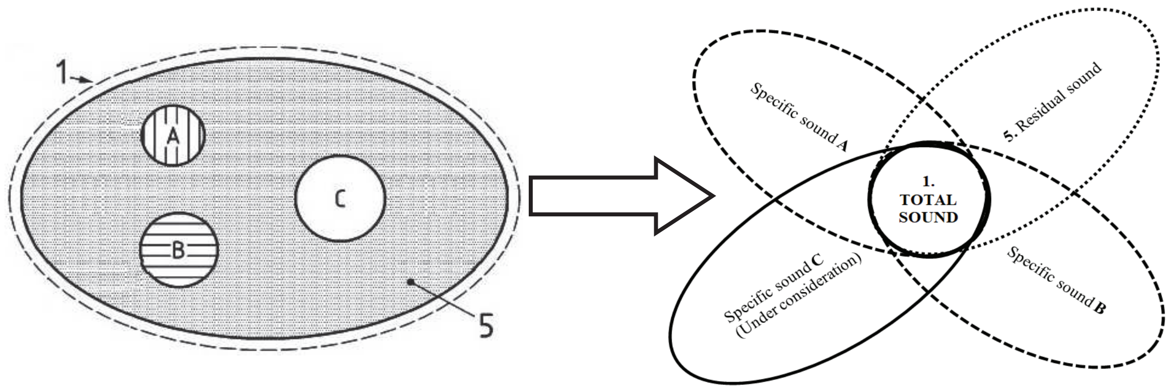

Figure 5 – Changing the point of view: ISO concept to the Venn diagram

This categorical logic permits a more convenient way of assessing the specific sound of ISO categorical propositions by drawing Venn diagrams, the idea showed in Fig. 5 is fairly straightforward, and the particular affirmative proposition asserts that the total sound is a member of all classes. Mathematical thinking of the total sound simplified like a set collection, allowing it to be considered through a possible computer program, with low complexity by discrete mathematics. Equation 1 shows the *total sound* as an intersection subset, and it is the results of overlapping the others:

$$\textit{Total sound} = \textit{Residual sound} \ \cap \ \textit{Specific sound}\ \mathrm{A} \ \cap \ \textit{Specific sound}\ \mathrm{B} \ \cap \ \textit{Specific sound}\ \mathrm{C} \qquad (1)$$

Using Eq. 1, one can estimate the specific sound as follow:

$$\textit{Specific sound C} = \{\textit{Total sound}\} - \{\textit{Residual sound} \cap \textit{Specific sound A} \cap \textit{Specific sound B}\} \qquad (2)$$

Eq. 2 shows the *specific sound* under consideration is the *total sound* when the others are excluded, it means that the specific sound should be appraised by a statistical level (such as L_{A90}), for instance, all the sound levels below these reference percentile belong to environmental *basal noise*, on the contrary they will be consider as outlier.

5.4 The “unwanted sound” as outlier sound events which need to be extracted

Fig. 6 shows the L_A time-history sound level each 125 ms like dots, instead of "seeing" it as a continuous line, the 60-minute interval between 6 pm and 7 pm, with a working plant. The noise emissions from the industrial facility under consideration are steady, so one can assume that the *environmental basal noise* (including the *specific sound*) is beneath a statistical value noise level.

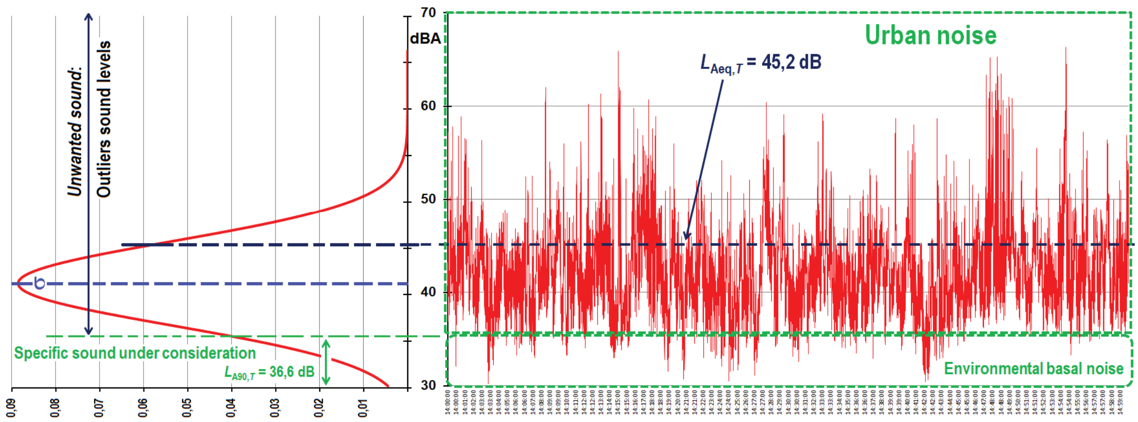

Figure 6 – Normal distribution of *total sound*: From 2 pm to 3 pm. Plant on duty

In order to explain the inferences, Fig. 6 shows the normal distribution curve of the measurement but rotated, because in this way it’s easy to see its positive skweness. It can be observed that there is a concentration of sound levels below L_{A90} (36.6 dBA), that should be appraised like the *specific sound*, so for statistical reasons if it is possible to remove the outliers sound levels, then one may considerer the L_{A90} value as a threshold of *unwanted sound* in order to exclude those spikes which don’t belong to the *specific sound* under consideration.

In Fig. 6, it is easy to see the *environmental basal noise* idea: The normal distribution curve doesn’t have values below 30 dBA, it is not truncated, and this is because it is the minimum sound level measured by SLM; this is the concept of environmental basal noise, so beneath the statistical L_{A90} value there are high probability to estimate the *specific sound* level under consideration.

5.5 Inference: Estimating the *specific sound* using a statistical percentile level

A practical way of appraising the possible sound pressure level of Fig. 6 measurement is to assume that the L_{A90} or L_{A95} have should been the "specific sound level," it means to use a single statistical value as the equivalent estimator.

Table 2 – Appraising the specific sound level considering one statistical value (re dB 20 μPa)

	Total sound level measured ≡ $L_{Aeq,T}$	Appraised #1 *specific sound* level ≈ $L_{A90,T}$	Appraised #2 *specific sound* level ≈ $L_{A95,T}$
$L_{Aeq,T}$	45.2	36.6	35.5
$L_{Ceq,T}$	59.7	unknown	unknown
$L_{Zeq,T}$	63.6	unknown	unknown

The issue is, which one of those two statistical values should be chosen as representative of the *specific sound*? Moreover, how should one know the low-frequency level or the infrasound level under this assumption? It is impossible to know them because it doesn't have the complete data of the whole *specific sound* time-history, but just one single "representative" value?

6. EMPIRICAL METHOD TO DETECT AND REMOVE THE OUTLIERS

This section is a brief explanation of the empiric method applied to develop the functions and procedures which were programmed into VBA computer language included in Excel®, because it is easy to use its large library for mathematic and statistical function, no further programming needed.

It is necessary to note that the Empirical method is applied to sound pressure levels data in *csv* format resulting to the measurement, not to sound wave.

6.1 Excluding the unwanted sound by means of outliers concept

The simplest procedure to exclude the unwanted sound, it is not consider those sound events which do not belong to the specific sound, removing them -statistically speaking- as if they were outliers.

There are a number of methods and algorithms to remove the outliers (8, 9, 10), for the particular procedure presented here, generating and separating a vector with the *specific sound* noise from the vector containing the total sound data, it will have to consider one threshold value (such as the statistical value L_{A90}) from which all the noise levels that exceed it shall be considered "outliers." The resulting vector contains the time-history of the *specific sound*, and it will be a "smooth signal."

Other authors (in the field of physics or other sciences) use similar procedure (9, 10), but instead of deeming it "outlier removal," they often use other synonymous terms such as "spikes removal," "removal of spurious," etc.

6.2 Inference: Estimating the *specific sound* using a statistical percentile level

A particular macro was written to obtain the equivalent-continuous sound pressure level (using the spreadsheet with the data measurement) in dBA, dBC and dBZ; the "Percentile" function included in Excel® was used to calculate the percentiles noise level. The Tab. 3 shows the final results:

Table 3 – *Total sound* level: From 2 pm to 3 pm. Plant on duty (re dB 20 μPa)

$L_{Aeq,T}$	$L_{A90,T}$	$L_{A95,T}$	$L_{Ceq,T}$	$L_{Zeq,T}$
45.2	36.6	35.5	59.7	63.6

The L_{A90} is the appraised value to be considered as an Estimator; in this case, using it as a threshold value from which each individual L_{A125ms} level exceed it, the L_{A125ms} will be removed from the file.

6.3 Resolving the mathematic empirical model by modular programming

The author presents in (6, 7) a similar set of procedures, in this Paper an updated version is presented. A new concept about modular programming has been incorporated, because a matrix structure is more flexible for Set Theory, which is the empirical idea to write automatic software for removing the outliers.

The SLM generate a data row, each 125 ms, so the resulting array represents a set containing 47 elements ($TS_{[i;j]}$ matrix) with the following format A=[Time stamp; L_Z; L_C; L_A; L_{10Hz}… L_{20kHz}], meaning there are 28,800 rows of 60-minutes' measurement. Accordingly, the element $A_{(i;4)}$ will always be the L_A value, because all the elements in row *i* column *4* are the L_A sound level of 125 ms measurement each.

6.3.1 Module A: Excluding the unwanted sound. Outlier's detection

This Module calculates the L_{A90} that it will be the threshold value. The simplest procedure to exclude the unwanted sound is to remove the spikes and not consider those sound events which do not belong to the specific sound. A decision structure asks whether each $TS_{[i;4]}$ value is greater than the threshold:

- If $TS_{[i;4]} \rightarrow L_A > L_{A90}$ threshold value: the program discard the actual row and goes to next one, it seeks the $TS_{[i+1;4]}$ asking again the same conditional.
- If $TS_{[i;4]} \rightarrow L_A \leq L_{A90}$ threshold value: the program copies its whole row into a $SS_{[i;j]}$ matrix, it seeks the $TS_{[i+1;4]}$ asking again the same conditional.

When the conditional doesn't find no more data in $TS_{[i;4]}$, the program activates Module B. So the only "filtering" used here is to exclude the outlier's spikes (11) which exceed the LA90 threshold value: <u>There is no frequency filtering</u>; therefore, what is being "filtered" is the L_A outliers contained in the total sound matrix file.

6.3.2 Module B: Building the specific sound time-history. ILFN tones identification

The building-processing algorithm uses the $SS_{[i;j]}$ matrix, which contains all L_{A125ms} values. The processing is performed consecutively in all 34 frequency one-third-octave bands between 10 and 20 kHz, this Module calculates the equivalent-continuous sound pressure level in dBA, dBC and dBZ; the "Percentile" function included in Excel® was used to calculate the statistical noise level. Tab. 4 shows the final specific sound results using the $SS_{[i;j]}$ matrix.

Table 4 – *Specific sound* level: From 2 pm to 3 pm. Plant on duty (re dB 20 µPa)

$L_{Aeq,T}$	$L_{A90,T}$	$L_{A95,T}$	$L_{Ceq,T}$	$L_{Zeq,T}$
35.3	32.6	31.5	54.4	60.6

Fig. 7-a shows the resulting *specific sound* time-history "built", it is a smooth line because all outliers and spikes belonging to the unwanted sound were removed.

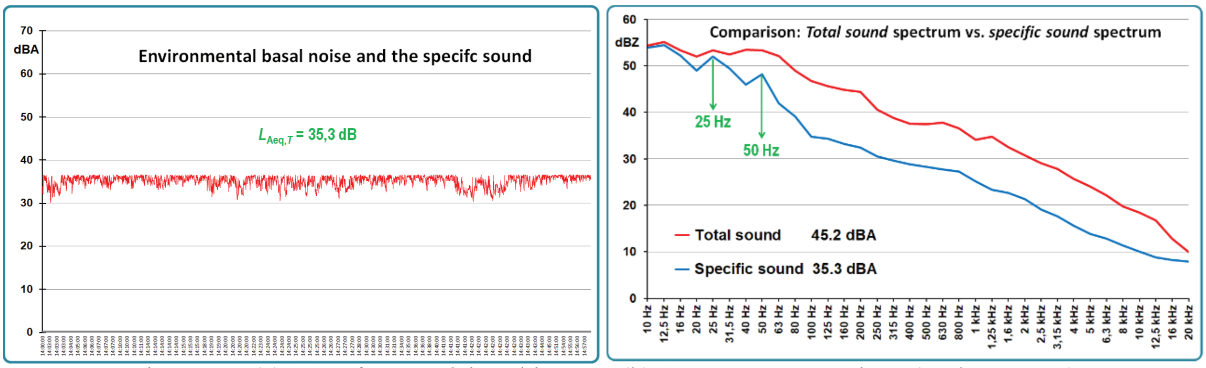

Figure 7 – (a) *Specific sound* time-history - (b) Spectrum comparison (re dB 20 µPa)

Fig. 7-b shows a comparison between the *specific sound* spectrum vs. *total sound* spectrum of the same measurement with plant on duty from 2 pm to 3 pm, where it can be seen how, after application of the empiric method to remove the outliers, two tonal sounds appear in low-frequency band (after running the outlier-removal program), those they were masked by urban noise; so, the real *specific sound* level in the low-frequencies band displays relevance, and the distinct tones contained in the spectrum can be found distinctively.

7. STRUCTURAL VIBRATION DUE TO GROUNDBORNE ILFN IMMISSION

In order to validate the empirical method as a tool to demonstrate the ILFN immission from the buried pipeline (that produce structural vibration), this empirical method was applied to the matrix containing the total sound measurement between 2 pm and 3 pm when the plant was out of service (off duty). Fig. 8 show two graphics: (a) it displays the time-history of the residual sound level, after applying the empirical method to *total sound* file presented in Fig. 8. (b) It displays a comparison between the *specific sound* spectrum with plant on duty (it registered on day #1) vs. *residual sound* spectrum with plant off duty (it registered on day #2).

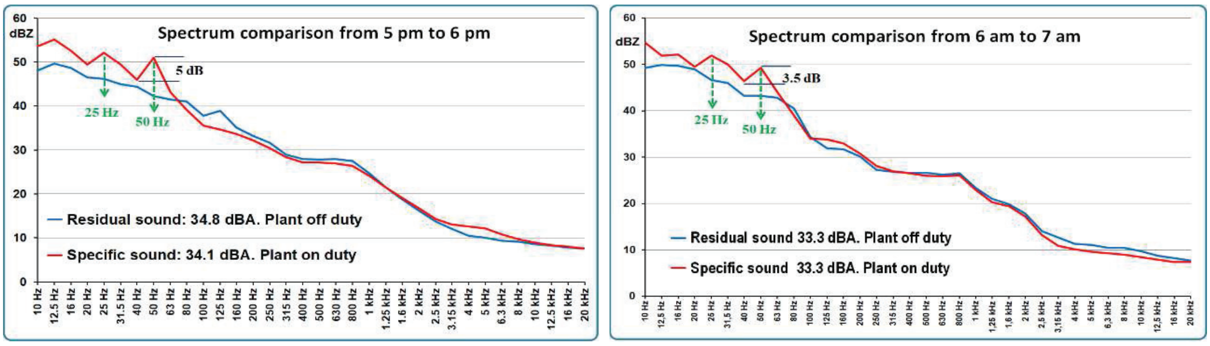

Figure 7 – Spectrum comparison on different hours. Plant on duty vs. off duty (re dB 20 μPa)

8. CONCLUSIONS

If an inexperienced person, or acoustician without proper training, would give the total sound level measured by the SLM like valid, the Report would be wrong because this value should not be informed like if were the noise level from the noise source under consideration. An even worse situation would be if one compares the total sound value in dBA against legal limits.

After using the empirical method, the assessment of LFN radiated from the house’s walls is more clear because of the structural vibration, and it was reported to the Authorities that: (a) the mechanical energy from underground pipeline that propagates through the soil is responsible for this phenomena. (b) Even the sound levels are below to legal noise limits, because of the low level of environmental noise, the LFN is possible to produce psychological disturbance but not physical diseases. (c) There is not airborne sound propagation from the plant to the house at 250 m distance. (d) It should be necessary to install some specific valves to control the affluent flows, in order to reduce their velocity.

This algorithm has been used efficaciously for more than seven years; so the purpose of this Paper is to share to the acoustician community that it is possible to achieve a standardized method in the sense that an algorithm could be agreed upon among specialists for having an “universal” computer program to determine the specific sound contained in the total sound.

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