UDC: 534; 331.45; 628.517.2
OECD: 01.03.AA; 10.63.49; 87.55.37

Low-Frequency Noise is underestimated by dBA. After 80 years, an LFN descriptor for rating annoyance is necessary

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Abstract

The dBA was defined in 1936 to measure low levels up to 55 dB; the oldest sound level meters included two panel switches: one for sound pressure and the other for frequency weighting. It became easier to measure just the dBA in late 60's, but this was not the best decision since low-frequency noise and infrasound are underestimated by dBA weighting. WHO recommends the use of dBC-dBA and suggests that when this difference is greater than 10 dB, an analysis should be applied. For more than 80 years, the common worldwide laws against noise have forced us 'to feel the noise in dBA levels,' which is not true because our body 'senses' the whole flat frequency bandwidth. Few countries have legislation on how to assess ILFN levels. This Article discusses the necessity to create a paradigm for LFN measurement (based on ISO 1996), in order to 'retire' the dBA noise descriptor.

Keywords: Low-frequency, noise descriptor, standards, audibility, philosophy of technology.

Низкочастотный шум занижается при применении дБА. Через 80 лет стал необходим дескриптор низкочастотного шума для оценки раздражающего воздействия

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Аннотация

ДБА был определен в 1936 году для измерения низких уровней до 55 дБ; самые старые измерители уровня звука включали два панельных переключателя: один для звукового давления, а другой для частотной коррекции. В конце 60-х годов стало проще измерять только дБА, но это было не лучшим решением, поскольку низкочастотный шум и инфразвук занижаются при коррекции дБА. ВОЗ рекомендует использовать дБн-дБА и предлагает проводить анализ, если эта разница превышает 10 дБ. Уже более 80 лет общепринятые во всем мире законы против шума заставляют нас "чувствовать шум на уровне дБА", что неверно, потому что наше тело "чувствует" весь плоский диапазон частот. Лишь немногие страны имеют законодательство о том, как оценивать уровни инфразвука и низкочастотного шума (ILFN). В данной статье рассматривается необходимость создания парадигмы для измерения низкочастотного шума (основанной на стандарте ISO 1996), чтобы "убрать" дескриптор шума дБА.

Ключевые слова: *Низкочастотный, дескриптор шума, стандарты, слышимость, философия технологии.*

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Introduction

The development of the first frequencies weighting curves in 1936 was a great scientific and technological effort, but it became as Standardized under Z24.3 in 1944 by ANSI. The 'A' frequency weighting was defined only for low sound levels up to 55 dB; the 'B' frequency weighting was defined for medium sound levels 55-85 dB, and the 'C' was defined for high sound levels upon 85 dB and it was flat, not frequency weighting at all.

The so-called 'A', 'B', and 'C' curves were 'approximate' the inverse of the 40-, 70-, and 100-phon equal loudness curves [1], they were defined in IEC 123 as International Standard in 1961, and a frequency weighting was established to 'C'.

The sound level meters used in those early years had two panel switches: one for sound pressure (attenuator in 10 dB step) and the other for frequency weighting. It called for the operator to be a trained person, because he had to adjust the attenuator switch for an on-scale deflection of the indicating meter [2]. The following is the direction on how to measure:

2.3 SELECTION OF WEIGHTING NETWORK. Many early noise criteria specified weighted sound levels, using this rule of thumb: "A" weighting for sound levels from 24 to 55 dB, "B" for levels from 55 to 85 dB, and "C" for levels from 85 to 140 dB. (The appropriate range was selected after a preliminary C-weighted measurement.) More recent opinions favor selection of weighting network on the basis of the type of noise measurement; for instance, "A" weighting is often preferred for speech-interference measurements, while "B" is recommended for surveys of traffic noise. In the absence of specific weighting requirements, it is usually helpful to take measurements on all three weighting networks. [2]

It is obvious that the operator had to deal with changing the switches at every moment, but at the end of the 1960s decade, everybody used the A-weighting only because of equal loudness human response to noise, this conduct being a consequence of measuring the occupational noise in dBA values no matter the noise level.

For many years, the sound pressure levels in dBA measurements was correlated with loudness and the human perception, in the sense of having a sound descriptor to describe the nuisance or annoyance because of noise, but that information was weak in cases when the infrasound or low-frequency noise level were high. James Botsford was one of the first acousticians who realized that with a lot of experimental data, publishing a Paper about it in 1969, that year being the milestone of starting an on-going discussion: The A-weighting frequency does not inform the real noise impact on people.

1. Science and early technologies to measure the sound level and the auditory response at low-frequency range

The interest in having a means to measure a sound wave for analysis purposes has been a concern for centuries. Greeks philosophers used strings to identify musical notes; Felix Savart (1791–1841) invented the *Sonomètre* to measure musical tones by strings resonance with weights circa 1827, and after that, a perforated wheel [3]; until 1878 many mechanical devices were developed using flames, mirrors, sirens, etc., when Thomas A. Edison (1847–1931) invented the *Phonograph* and recorded the Elevated train noise of New York City [4] for further analysis.

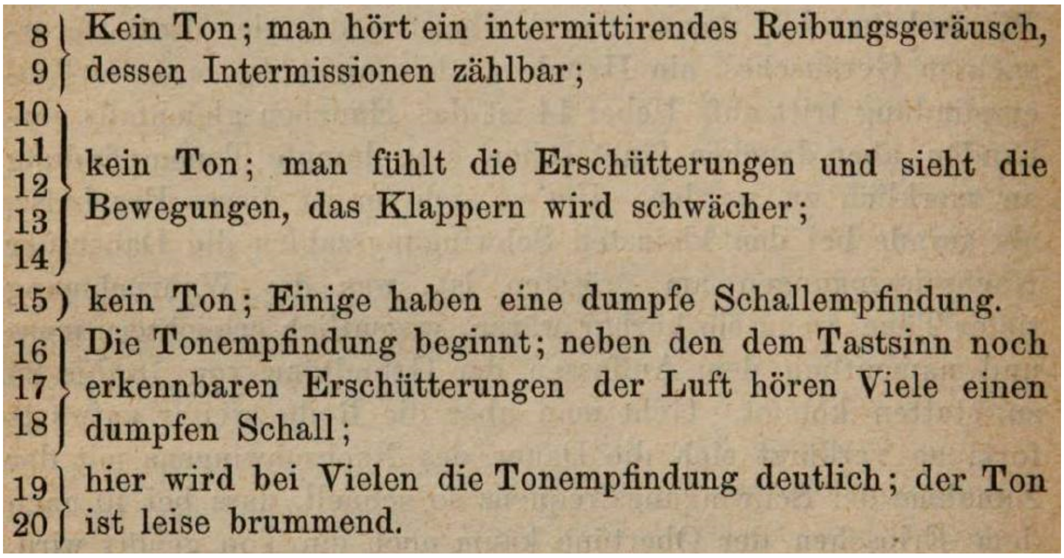
1.1. Seeking of one quantitative unit

1.1.1. Fechner and the psychophysics of auditory system

For centuries, many scientists had been saying it was impossible to describe the human sensations by quantification units. Gustav Theodor Fechner (1801–1887), a Philosopher dedicated to Psychophysics, was the first who elicited and conceptualized in 1860 that the *'auditory system hears in a logarithmic way'* [5], but the right instrumentation didn't exist to verify that.

1.1.2. Preyer and the limits of the perception of tones

William Thierry Preyer (1841–1897) was one of the first who studied systematically the hearing of lowest tones; he published his investigation in 1876 *'On the limits of the perception of tones'* [6], he used very deep, loaded tongues, in reed pipes, to produce bass tones from 8 cps; he reached the next astonishing conclusions after many repetitions:



8, 9: Kein Ton; man hört ein intermittirendes Reibungsgeräusch, dessen Intermissionen zählbar;
10, 11, 12, 13, 14: kein Ton; man fühlt die Erschütterungen und sieht die Bewegungen, das Klappern wird schwächer;
15: kein Ton; Einige haben eine dumpfe Schallempfindung.
16, 17, 18: Die Tonempfindung beginnt; neben den dem Tastsinn noch erkennbaren Erschütterungen der Luft hören Viele einen dumpfen Schall;
19, 20: hier wird bei Vielen die Tonempfindung deutlich; der Ton ist leise brummend.

Fig. 1. Compilation of observed perception of bass tones vibrations (Preyer, 1876)

Preyer didn't use any instrumentation to do the measurements *'These were set into strong vibration by blowing, and then on interrupting the wind, the dying off of the vibrations was listened to by laying the ear against the box'*, he wrote the sensation that they felt [6]:

a) 8-9: No sound; one hears an intermittent friction noise, the intermissions of which are countable.

b) 10 to 14: no sound; you feel the vibrations and see the movements, the rattling becomes weaker.

c) 15: no sound; some have a dull sensation of sound.

d) 16 to 18: The sensation of sound begins; in addition to the vibrations of the air that can still be felt by the sense of touch, many hear a dull sound.

e) 19-20: here the sound sensation becomes clear to many; the sound is humming softly.

There are more conclusions in his publication, but for this article the most important issue to bring out is his pioneering work on the human hearing sensation in infrasound and low-frequency sound region.

1.1.3. Helmholtz and the earliest studies on low-frequency hearing

Hermann L. F. Helmholtz (1821–1894) published the first edition in German his influent book *'On the sensation of tone... '* in 1863, and the final edition in 1877, for this article, the English translation of the last one [7] was used. For the first experimentation (in 1862 before Preyer) Helmholtz used a Savart wheel, long organ tubes and other primitive resources, but he could not generate frequencies below 30 vibrations (cps) free of distortion or upper partial harmonics, but he did experience 24 vibrations (cps).

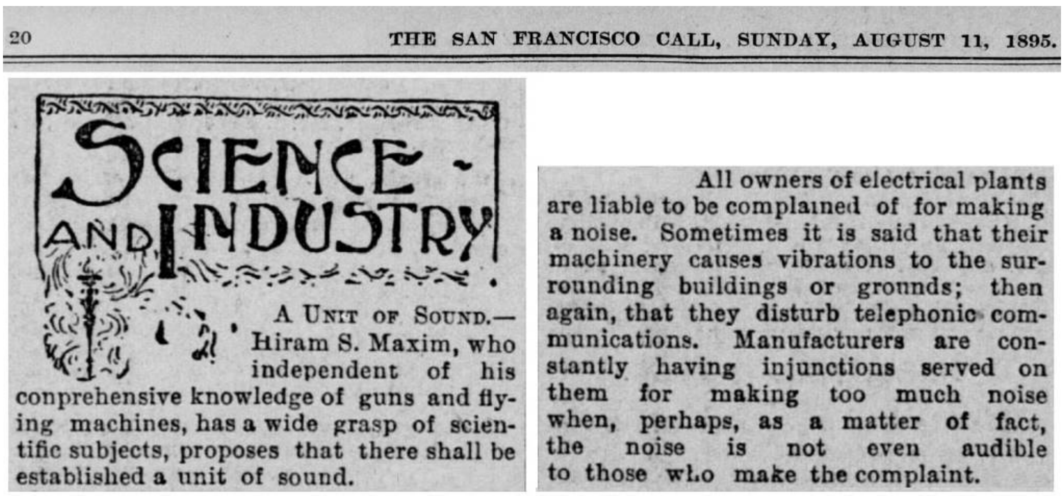
It is interesting that in the English version of this book, the translator (he was an expert into acoustics) in 1877 after Preyer' is replicated his experimentation because Preyer asked to, and the translator used similar apparatus as well as Prayer in order to check out the right frequencies' vibrations. The translator improved the Helmholtz book, because he made a correlation between the Helmholtz results and the Preyer one.

1.1.4. Hartmann and the hearing test on a graphical representation

The German otologist Arthur Wilhelm Hartmann (1849–1931) in 1889 published an important book *'Die krankheit des ohres und deren behandlung' ('Ear disease and its treatment')* [8]; in its Chapter 4 *'Hearing test'* he analyzed different hearing responses of metal workers by putting in a graphical representation for the results of their hearing test (first conceived by himself in 1885), using eight tuning forks for the experiment; he pointed out the use of wood box for amplifying the sound intensity of lower frequency forks in order to maintain the equal hearing sensation. It was not until the invention of the valves in 1906, that the sound levels could be accurately measured.

1.1.5. Low-frequency noise nuisance in 1895 Newspaper article

The nuisance and annoyance produced by low-frequency noise began with the use of big machinery, such as boilers, steam machines, electric generators, etc.; it is interesting how he people react to the 'unheard noise' produced by these new technologies. In 1895, the following article was published a newspaper [9]:



20 THE SAN FRANCISCO CALL, SUNDAY, AUGUST 11, 1895.

SCIENCE AND INDUSTRY

A UNIT OF SOUND.—Hiram S. Maxim, who independent of his conprehensive knowledge of guns and flying machines, has a wide grasp of scientific subjects, proposes that there shall be established a unit of sound.

All owners of electrical plants are liable to be complained of for making a noise. Sometimes it is said that their machinery causes vibrations to the surrounding buildings or grounds; then again, that they disturb telephonic communications. Manufacturers are constantly having injunctions served on them for making too much noise when, perhaps, as a matter of fact, the noise is not even audible to those who make the complaint.

Fig. 2. Low-frequency noise mentioned in 1895 (extraction)

This article is remarkable because the famous Hiram Stevens Maxim (1840–1916) was called to attend that problem about low-frequency noise. It is obvious that in 1895 they couldn't identify the frequencies range responsible for the nuisance, but they pointed out *'the noise is not even audible'*. [9]

1.2. Earlier studies on human hearing at infrasound and low-frequency region

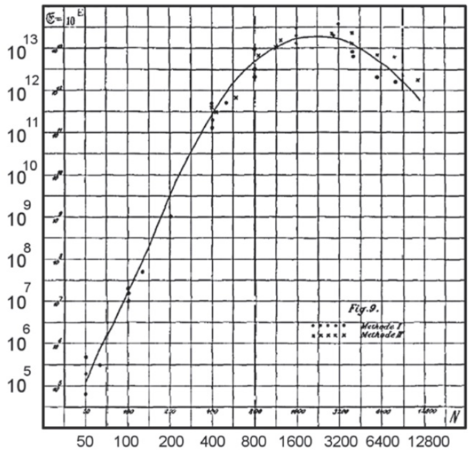
1.2.1. Relationship between hearing thresholds and frequency. Wien's work

Max Wien (1866–1938) made an early measurement of the lower limit of sound intensity that is audible, and his research brought several advances on how to understand the auditory sensations in the lowest audibility region; additionally he was the first who could demonstrate the de Fechner Principle that the auditory system hears in a logarithmic way.

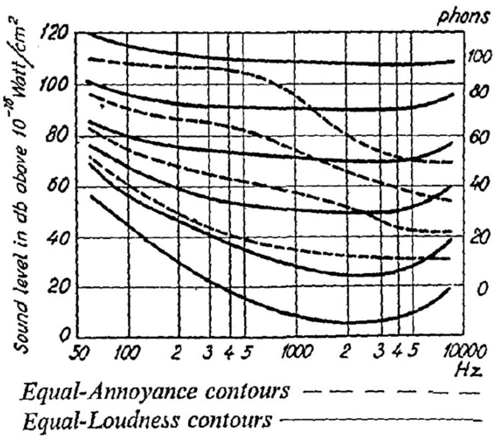
Wien published a Paper with his research in 1903 titled *'About the sensitivity of the human ear to sounds of different heights' ('Ueber die empfindlichkeit des menschlichen Ohres für töne verschiedener Höhe')* [10], he analyzed three different telephone's devices.

Wien used a telephone receiver to measure absolute intensity thresholds, and an alternating current siren –as sound source– to generate a periodic current change in order to determine this sensitivity at different frequencies. In the experiment, the current amplitude was first reduced until no sound was heard, and then increased again beyond the threshold of perception; Wien, therefore, goes over to logarithmic sensitivity with base 10.

Wien first carried out a frequency-independent shift of the sensitivity curves obtained. The chart shows the relationship between hearing thresholds and frequency, as one can see in Figure 3-a.



(a)



(b)

Fig. 3. (a) Sensitivity of the human ear as a function of frequency (Wien, 1903);
(b) Equal loudness contours (Laird & Coye, 1929) taken from [11]

Wien also thought about *'what would happen to the sensitivity values for hearing impaired people?'* He was already thinking of using its apparatus to diagnose hearing loss.

1.2.2. Laird and Coye and the pioneer research on low-frequency hearing

At Colgate University, the investigations of two psychologists Donald Anderson Laird (1897–1969) and Kenneth Coye (?–?) were focused on how different stressors affected people at workplaces, among them noise was a central subject. They published in the first issue of ASA's Journal in 1929 *'Psychological measurements of annoyance as related to pitch and loudness'* [11], a complete work and the first of its kind, analyzing, and put together in one graphic the equal loudness contour and the equal annoyance contour, as one can see in Fig. 3-b. The importance of some of their studies is the observation on the annoyance of low levels of low frequency-noise at workplaces.

1.2.3. Von Békésy on the tactile sensation vs hearing at infrasound and low-frequency region

Georg von Békésy (1899–1972) is considered to be the first to publish a complete audiogram on human hearing covering the infrasound and low-frequency sound region; he succeeds in perceiving a tone of 1 Hz in human hearing threshold tests done in 1936; at such low frequencies, Békésy discovers a relationship between 'audible stimuli' and 'stimuli that can be felt by touch' [12]. Von Békésy found discrepancies on the absolute threshold in a previous investigation of the perception of sinus tones at the border to infrasound, which suggests an explanation by hierarchically-organized neuronal oscillations. He contributed significantly to the understanding of the production and measurement of low-frequency sine waves on the one hand and the perception on the other.

1.3. The beginning of Electroacoustics Era: The first condenser microphone for sound measurements

Since the invention of the microphone used for the telephone communications, a lot of scientists tried to adapt it for sound measurements, but they had a poor quality because of the magnetic coupled. Edward Christopher Wente (1889–1972) working at Bell, designed and patented in 1917 [13] a condenser microphone with: plus 15 kHz bandwidth, undistorted and flat response, with real possibilities of calibration, electric circuit stability.

The *'Wente microphone'* measures any kind of arbitrary noise in Sound Units intensity and was capable of dealing with low levels of sound using an internal valve to amplify the voltage delivered by the membrane. For the first time, the acousticians could measure the minimum audible sound. This microphone was used for acoustic instrumentation, and it was applied for more than 50 years as the Standard reference. One version has worked as a master transducer in an artificial ear, also.

2. Barkhausen: The inception of Phon concept and the dawn of sound level meters

The German scientist Heinrich Georg Barkhausen (1880-1956) worked on different physics areas, and during the 1920s he concentrated on electroacoustics [14]. His goal was to make an apparatus which could measure the sound levels in terms of sensation. In Barkhausen's time, the sound pressure in Europe was measured in 'Wien' (named in honor of physicist Max Wien); its scope ranges from '1 Wien ≡ hearing threshold' to '16,000 Wien ≡ pain thresholds.' To push this area onto a manageable scale, Barkhausen used -according to Fechner- the logarithm to base 2: Doubling of the volume impression resulted in an increase of his point by one point. *'I would like to suggest the term 'Phon' for this volume unit'* [15]; and with that, the 'Barkhausen-Phon' was created.

The concept of Phon as measure unit was finally internationally accepted in June 1937 at the first *'International acoustical conference'* [16] which took place in Paris, but its actual concept as magnitude is totally different to that one.

There are a lot of publications about the use of Barkhausen's phonometer in sound intensity measurement, and it was extensively used for acoustic isolation measurement until the 1950s. The 1931 version was the most precise model (under the Siemens trademark), and its characteristics were replicated by some US companies, but in 1933 because of its German origin, in the US its use was banned.

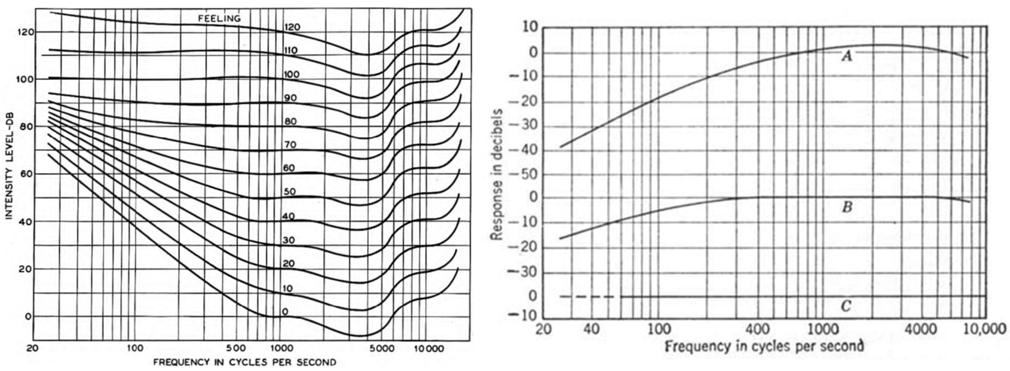
3. Fletcher and Munson equal-loudness curves

Harvey Fletcher (1884–1981) joined Western Electric Company in 1916, and he was more interested in the acoustics field -specifically on speech and human hearing- than telecommunication. It is important to note that at the same time of Fletcher's work at Bell (in America), Barkhausen was working in the same field but at Siemens (in Europe), and their works were quite similar with some differences between them.

Fletcher together with Wilden Andrew Munson (1902–1982) have done the first important research on hearing sensitivity and loudness in 1933 [17], with certain limitation but it was revolutionary during those years. Although the previous research on low-frequency hearing (one of them published in the first ASA Journal by Laird&Coye), Fletcher and

Munson did not take care about it: *'Note that as Fletcher informally observed, the loudness of low-frequency comparison tones changed more rapidly with changes in the level of the standard tone than did tones in the mid-frequency range near the 1000-Hz standard'.* [18]

It is well known that in two important issues of that research: **(a)** they used single sine waves as signals at different levels, in order to get the answer about loudness from the subjects under study, and **(b)** for hearing the signals, subjects used sealed headphones on their heads; **(c)** the responses curves do not take account the torso and human head frequencies filtering of the sound field.



(a) (b)

Fig. 4. (a) Loudness level contour (Fletcher&Munson, 1933);
(b) Z24.3-1944 frequencies weighting curves (Beranek, 1954)

For drawing the final level contour, Fletcher and Munson selected empirically the data but from those subjects who showed a *'normal hearing'* for each ear independently [17]. So, under this *'a very unnatural way to listen to a very unnatural sound,'* the A-weighting frequency was born.

4. From ANSI Z24.3-1936 to IEC 61672-1:2013

4.1. ANSI Z24.3-1936 and the initial frequency weighting curves

On December 27, 1928 at the Bell Telephone Laboratories in New York City, approximately 40 scientists and engineers interested in acoustics founded the Acoustical Society of America (ASA). In May 1932, a specialized Sub-Committee was formed in order to work on noise measurement. They developed in 1936 the *'Z24.3 American tentative standards for sound level meters for measurement of noise and other sounds'.* Although the Fletcher-Munson curves were published in 1933, their shapes were too complicated for using with analog technology, so the following weighting curves were proposed (See Fig. 4-b):

a) 'A' frequency weighting was conceived only for low sound levels up to 55 dB, and was from the 40-dB equal-loudness contour modified by the difference between random and normal free-field thresholds [19];

b) 'B' frequency weighting was conceived for medium sound levels 55-85 dB, the response curve was between that of A-weighting frequency and a flat frequency response.

c) 'C' was defined for high sound levels above 85 dB, with equal response over entire range.

After several attempts, the Standard Z24.3 for sound level meters was published in 1944 [20], with a small adjustment to 'A' and 'B' curves and the 'C' remained as flat. Contrary to the general thinking, the response to the frequency of the Standardized weighting curves does not approximate the Fletcher-Munson curves; they do not have 'reciprocity' as one can compare in Fig. 4. Houser [18] shares a really interesting comment:

It is crucial to recognize, and is evident in the evolution of sound level metrics, that the work at Bell Labs involving sound was focused almost entirely on telephone communication, and not on general principles of hearing. [18]

4.2. Technical references about the weakness of A-weighting to measure loud noises, complex sound or with low-frequency contents

Since almost the beginning of use of the weighting curves, acousticians realized that the A-weighting did not 'communicate' the real noise loudness. For instance, in 1938 Blair Foulds published a Paper *'Recent advances in the use of acoustic instruments for routine production testing'* [21] in which he proposes the sound level meters as a tool to identify the quality of the mechanical motors, but one of his observations is really remarkable:

Whereas the noise meter is intended to measure the level for loudness of a sound, the human observer not only gets the loudness of the entire sound but involuntary analyzes the sound (...) the overall loudness of a motor is controlled largely by the low frequency component and does not reflect small changes in mid or high frequency ranges. [21]

We have to take into account that paper was published just two years after the introduction of the first weighting curves (for sound level measurements with instruments).

Leo L. Beranek (1914–2016) in his influential Book *'Acoustics'* published in 1954 has pointed out *'It is emphasized that although these weighting networks are useful in giving the loudness level of pure tones, they are not able to give the loudness level of complex noises'*; [20] and it is clear that the dBA it was not defined to measure compounded sounds in its spectral shape, and it is inadequate for sounds with discrete tonal components or sounds with high levels of low-frequency characteristics.

Clayton L. Stevens in his Paper *'Filter Networks'* [22] written in 1957, he provides very interesting technical opinions: Extensive work has been performed and reported by many trying to find a workable formula for equating the sound pressure levels recorded using the A, B, and C networks to loudness levels. All efforts have resulted in essentially the same findings: that the readings can be useful only if the noises measured were simple sounds of one predominant frequency. (...) Past performance has proved that the A and B weighting networks can only be used in a few specific applications. [22]

Houser wrote [18] in reference to similar situations:

A-weighting is largely derived from studies of human listeners utilizing tonal signals and likely does not fully capture the relationship between complex signals and perceived loudness. It does not account for the frequency spectra of signals and likely underestimates contributions of complex signals across the frequency range of hearing.

4.3. IEC 123:1961 the first international Standard for sound level meters

IEC/TC 29 group was established in 1953, following the first *International Congress on Acoustics*, at which the urgent need for international standardization in electroacoustics was recognized, and at which time some topics were discussed in detail and some working draft documents produced. These were completed at the first meetings of TC 29 in The Hague, in 1953 [23]. After several discussions, in 1961 the first international Standard was published for sound level meters. The IEC 123 was a *Recommendation* with the objective to specify the characteristics of equipment to measure certain weighted sound pressure levels.

The 'A' and 'B' curve had almost the same weighting frequency as ANSI Standard, and to the 'C' at low frequencies and high frequencies a weighting was added. It is important to note that IEC 123 stated in its clause 4.3: *'Although these weightings approximate very roughly certain properties of the ear, they are to be considered merely as conventional'.*

4.4. The path through different Standards toward the IEC 61672-1:2013

For this Paper, the objective is not to explain these Standards, but to extract the concepts that the dBA is not a curve that simulates the human hearing response, for instance:

a) IEC 179:1973, states in clause 4.3: *'Although the curves A, B and C take certain properties of the ear into account, they must be considered to be purely conventional'.*

b) IEC 651:1979, states in clause 2.3.3: *'In the past, frequency weighting and time weighting have been associated with certain characteristics of the ear. However, recent work has not substantiated these historical associations so that frequency and time weighting characteristics of sound level meters may be considered to be conventional. The A weighting characteristic is now frequently specified for rating sounds irrespective of level and is no longer restricted to low sound levels'.*

c) IEC 61672 First Edition was published in 2002, and it does not say anything about the origin of statement of the A-weighting, the 'B' curve was eliminated and a 'Z' or flat frequency response was added.

d) IEC 61672 Second Edition was published in 2013, and it does not say anything about the origin of statement of the A-weighting.

4.5. The ISO 1996-1:2016 Third Edition

It is important not to forget the most important international Standard about noise measurement, the ISO 1996; it states in 6.2 Frequency weightings [24] *'Frequency weighting A is generally used to assess all sound sources* **except** *high-energy impulsive sounds or sounds with strong low-frequency content'.* (The underlines were made by the author)

5. Robinson and Dadson curves and the ISO 226

After the Fletcher and Munson publications, several researchers have published different concepts of the loudness or the human sensation (like Stevens, Newman, Zwicker, etc.). However, it wasn't until 1956 that a precise investigation was published. Donald William Robinson (1920–1999) and Robert S. Dadson (1908–?) did a controlled research in England on human hearing in free field conditions (with a frontal sound incidence of pure tones via a center loudspeaker in an anechoic room) titled *'A Re-determination of the Equal-Loudness Relations for Pure Tones'.* The equal-loudness contours known as Robinson-Dadson curves, map intensity in dB SPL to loudness-related log-like measure phons [25] (but not in *'Barkhausen-phon'* directions).

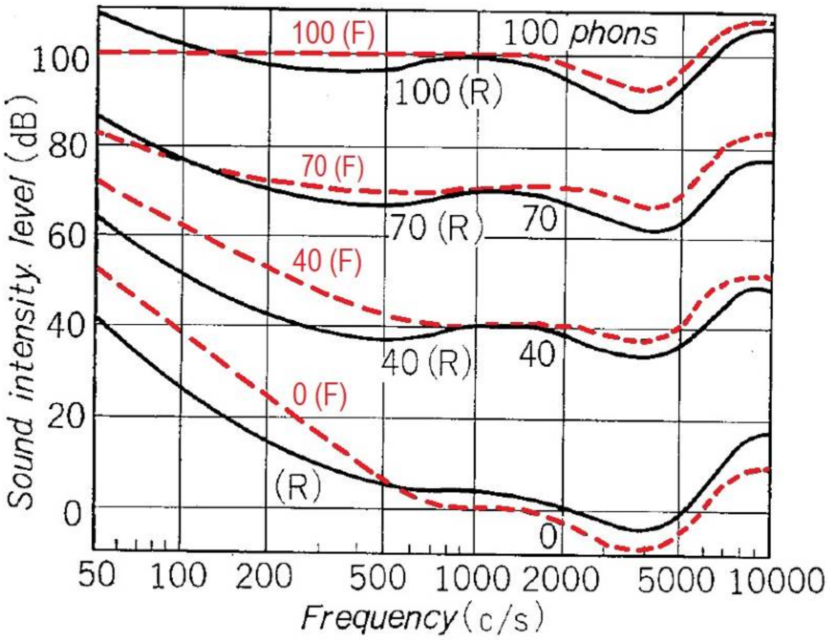


Fig. 5. Loudness level contour comparison: Fletcher-Munson **(F)** Robinson-Dadson **(R)**

The Robinson-Dadson equal-loudness contours curves are so different from the Fletcher-Munson equal-loudness contours curves, as one can observe in Fig. 5 (from [26]).

The Robinson–Dadson curves were used for the first international standard of loudness and hearing: the ISO 226 was published as a Recommendation in 1961. Möller analyzes the line-life of this Standard [27], and for its First Edition he wrote:

The data of ISO R226:1961 were based on a comprehensive investigation made by Robinson and Dadson. Their experiments included up to 120 test subjects and covered the frequency range 25 Hz-15 kHz and levels up to 129 dB. The main part of the experiment was made in a free-field environment, but at low frequencies the listeners were placed with head and shoulders inside a duct, which established a free progressive wave. As seen from the frequencies and levels covered by the investigation, the data of ISO R226:1961 at the lowest frequencies and at the highest levels must have been extrapolated. [27]

About the Second Edition of the ISO 226 published in 1987, Möller wrote: Despite of the changes, the data material was virtually unchanged but the upper frequency limit had been lowered from 15 kHz to 12.5 kHz, and the dynamic range had been restricted to 120 dB at low frequencies, 110 dB at middle frequencies and 100 dB at the highest frequencies. Evidently, doubt must have been raised about the data at the highest frequencies and at the highest levels of the former version. [27]

For the Third Edition of the ISO 226 published in 2003, the lowest frequency was the same of previous versions (20 Hz) and it was used for pure sinus tones also. The equal-loudness contours values below 1 kHz are much higher than previous ones, but the most important issue of this Edition is that the data used came from different countries.

6. The 1960s, decade of the universalization of the dBA as a single descriptor for human response to noise

Although the A-weighting frequency was defined to measure sound levels between 24 and 55 dB, there are dozens of research and publications in the 1960s about noise and loudness perception in homes, offices, and workplaces using the dBA with higher sound levels. Several statistics investigations on people that were exposed to broadband noises showed that a high levels of those with the analysis done by means of loudness instead of sound pressure level.

It shows a good correlation between the A-weighting frequency responses to approximate the human ear's response to a broadband noise with no tonal components.

In 1966, Karl David Kryter (1914-2013) talked about *'measuring the sound level in terms of loudness'*, and that ranking or rating the acceptability of real-life sounds should be made in terms of their loudness. He wrote this in a Report to NASA: While this is undoubtedly true, it overlooks the possibility that other basic attributes of a sound, such as pitch, complexity, etc., might interact with loudness to produce different judgments of acceptability than loudness alone. Indeed, as we shall see later, such an interaction does apparently take place. [28]

This Report was conducted by the Bolt, Beranek and Newman Company.

Another important issue about this simplification of the A-weighting frequency (no matter the sound levels) is that the researchers were using pure tones:

When used with individual pure tones, one would expect the sound level meter to give reasonably good estimates of loudness. One might feel, however, that this would not be true for more complex sounds. Nevertheless, as will be demonstrated later, when the network with 40 phon weighting is used with broadband sounds in the region from perhaps 60 to 100 phons, the obtained reading agrees reasonably well with judgment data of the loudnesses if the energy of the sounds is concentrated in the frequency regions below 500 cps or so, or above 2000 cps or so. The validity and use of the sound level meter with weighting networks for the evaluation of noises will be discussed below. [28]

It is clear that: **(a)** the *'network with 40 phon weighting'* is the A-weighting frequency, and **(b)** they are talking about the ear response at low-frequency, *'the obtained reading agrees reasonably well with judgment data of the loudnesses if the energy of the sounds is concentrated in the frequency regions below 500 cps or so'*. He mentioned some statistics results but using motor vehicles as a noise source:

It should be noted in figure 19 that in these experiments in which the subjects were asked to rate only the sounds from motor vehicles, dB(A) is often as good or better a predictor of judged loudness or noisiness (except when the vehicles were diesel-powered trucks) than phons(Z), phons(S), or PNdB. The ability of dB(A) levels to predict the subjective ratings of motor vehicle noise is perhaps partially due to the homogeneity of the spectrum of the sound. The spectrum of the sound from these vehicles is always predominantly in the frequency region below 500 cps or so. [28]

Throughout the whole Report, the sound levels compared pressure measures (dBA and dBC) against sound loudness measures. Perhaps the goal was to know the deviation of using different descriptors on the same noise. The most 'amazing' conclusion of the Report is *'On logical grounds, dB(C) and dB(A), being single measures taken over all frequencies, should perform the worst of the objective methods in estimating subjective loudness or noisiness...'* [28].

7. Botsford and his pioneer work on analyzing the content of low-frequency level by means of C-weighting and A-weighting frequencies together

Howard James Botsford (1925-1984) worked in the steel industry and was worried about human exposure to high sound levels. Among his jobs was a governmental Consulter for noise problems. In 1969, he published the most influential Paper about creating a noise descriptor for analyzing the low-frequency noise problem; the ASA comments in his Obituary [29] were:

Use of the A-weighted sound level was further developed in his paper *'Using Sound Levels to Gauge Human Response to Noise,'* where its relationships to hearing conservation criteria, speech interference levels, annoyance of neighborhood noise, desirable sound levels in rooms, and perceived noise levels were established.[29]

Knowing the amount level of low-frequency content in a sound spectrum, in terms of sound pressure, that was not unknown, was noted by Beranek in 1954:

Readings are usually taken with each of the three weighting networks. From these readings, information regarding the frequency distribution of the noise can be obtained. (...) if the sound level is greatest with network C, the sound predominates in frequencies below 150 cps. [20]

Botsford after analyzing 953 different spectral noise measurements registered at different industries, he obtained from the measurement in 1/3 octave bands the L_A and L_C values, observing a particular behavior: when the value of the difference between the C-A was high, that index is correlated with acoustic emissions with high energy content at low-frequencies. His conceptual idea of using C-A difference value, is transcribed in Community Noise (published by WHO in 1995) *'... it is suggested to use: sound pressure level in dBC and dBA and their difference as a first estimate of the low frequency content... '* [30].

8. The problems of measurement using the dBA take place among acousticians

8.1. Are our noise laws adequate?

In 1973, an interesting Paper was published by M.E. Bryan and W. Tempest: *'Are our noise laws adequate?'* [31], about not using the data resulting from experimental research on noise annoyance using dBA measurements (among other issues):

This exclusion has been made because the laboratory experiments seem to be almost totally unrelated to the real-life situation; the laboratory listeners are voluntary, and are short-term, the noise will finish when they go home, and they are being asked to express an opinion as to the relative noisiness or unpleasantness of a range of sounds. [31]

They analyzed some noise descriptor (PNdB, Traffic Noise Index, etc.) mentioning a 1968 study *'Subjective response to traffic noise'* with the following statement:

Individual dissatisfaction scores correlated poorly with physical measures. This finding is believed to be the result of wide individual differences in susceptibility to and experience of noise, as well as patterns of living likely to be disturbed by noise. Attempts to allow for these factors were unsuccessful. [31]

They share some concepts from a 1969 survey about traffic noise done by D.W. Robinson *'Whilst noisiness ratings were related to the average measures of loudness level and overall level in dB(A), they did not provide a reliable guide to the probable acceptability of the noise climate.'* [31] Finally, they comment on a traffic study done by Salsford University in 1971: The survey results are presented in Fig. 3, which shows annoyance rating against external noise level in dB(A). (...) This data provides evidence that the Noise Advisory Council's recently suggested (L_{10}) 70 dB(A) maximum permitted noise level for houses adjacent to motorways will be unsatisfactory. [31]

They show evidence that the psychological conditions of the sensitive people to noise are important, but sometimes the noise limits in dBA values are not conclusive, and it should include some other spectral components *inside the noise* which provokes an annoying condition under some circumstances on people.

8.2. The first international colloquium concerning infrasound only, 1973

The first international colloquium concerned with infrasound only was held in Paris in 1973, organized by Leonid Pimonow (1908-2000). It was the first time that acousticians discussed the infrasound and low-frequency noise problem, and the inadequacy of using the dBA for their analysis [32]. Since then, a long journey has started for several researchers to establish a noise descriptor apart from dBA to assess the low-frequency noise.

9. Broner and Leventhall: Their researches and publications about ILFN

Despite the existence of several specialists on ILFN (to the author's criterion), Dr. Norman Broner is the most remarkable researcher with his contributions on how to analyze the low-frequency problems. Among his dozens of investigations, in 1978 *'The effects of low frequency noise on people - A review'* with a complete resume of other researchers [33] about ILFN annoyance, effects, criteria, etc. was published. They have proposed a low-frequency noise rating curves in 1983 [34] to assess this phenomenon.

They analyzed many low-frequency noise complaints (also 700 letters sent to the 'Sunday mirror'). The Introduction of their Paper offered:

It is becoming increasingly apparent that the SPL(A) value is not a valid basis for validating a complaint where the intruding noise is unbalanced, so that it contains most energy in the lower frequencies. (...) It is, therefore, apparent that annoyance due to low frequency noise is experienced by members of the general population. Now that the problem has been recognized, more complaints are coming forward. [34]

They add a comment on loudness perception: *'The common assumption that the assessment of loudness and annoyance are equivalent also breaks down in these cases (Tempest, 1973: Bryan, 1976) and this may be due, in part, to the unsteady nature of much low frequency noise.'* [34] Fig. 6 presents the proposed Low frequency noise rating curves.

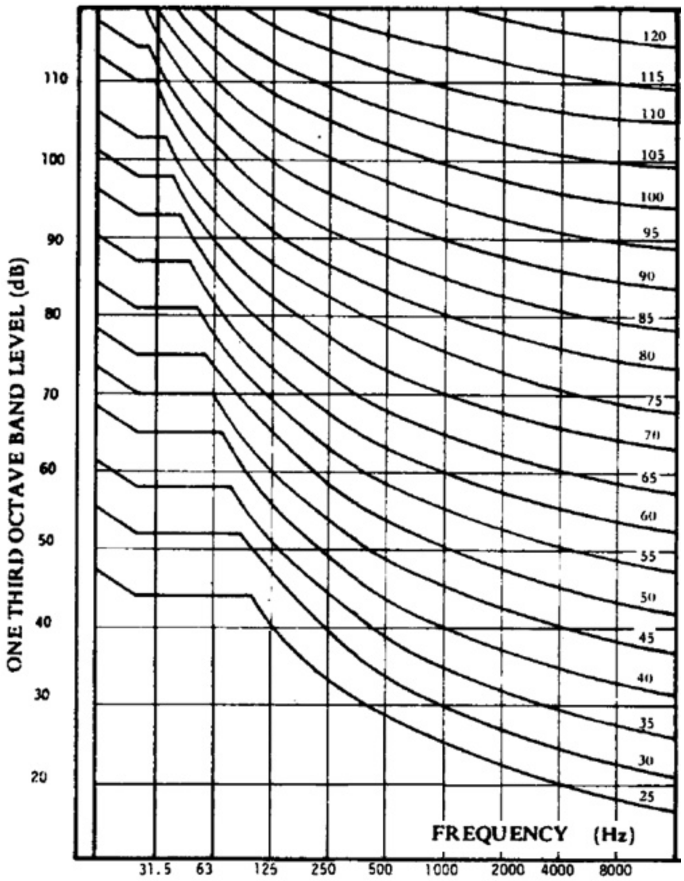


Fig. 6. The proposed Low frequency noise rating (LFNR) curves (Broner, 1983)

The conclusion of their publication on LFN annoyance assessment is:

Low-frequency noise annoyance problems are more common than originally believed and are becoming increasingly recognized as awareness of the problem develops. (...) It is necessary to measure the annoying noise in the environment concerned, not externally as recommended by most guides and standards. [34]

10. Analyzing dBA measurements with low-frequency content

This chapter will present a few of the most emblematic cases that the author has encountered in his professional work (at least 85 similar cases in 15 years) where the impact of low-frequency noise was important, and it demanded a specific acoustics analysis because the C-A level in those cases was lower than 10 dB but the presence of the predominant tonal characteristics was important or a low-frequency sound was possibly heard (like a buzz or hum, i.e., annoying noise). The following instrumentations for sound measurements were used:

a) Sound level meter analyzer with one-third-octave band, CESVA instruments, a class 1 SC420 model. Digital audio recorder, a portable sound recorder ZOOM H1.

b) Sound level meter analyzer with one-third-octave band, CESVA instruments, a class 1 SC310 model. Digital audio recorder, a portable sound recorder ZOOM H1.

c) Sound level meter analyzers with one-third-octave band, BSWA instruments, a class 1 308 model. Digital audio recorder, a portable sound recorder ZOOM H1.

d) A class 1 sound calibrator, CESVA CB005 model.

10.1. Case 1: Hospital‘s intermediate recuperation room

For the installation of HVAC equipment due to the expansion of the MRI room (on a second floor roof), they did not take into account their proximity of the intermediate recovery rooms on the fourth floor of the same building. The nursing team received many complaints from patients in which a persistent buzzing noise did not allow them to rest, mainly during night hours. The following graphics show the sound measurement inside of one patient room, using the time history (Fig. 7-a) in which the intervals of the HVAC noise alone had to be extracted, and their frequencies spectrums analyzed (Fig. 7-b).

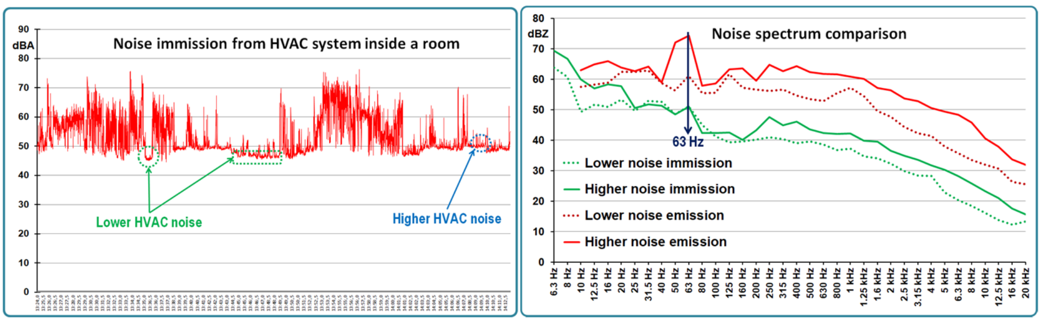


Fig. 7. Sound pressure level inside an intermediate recuperation room (re dB 20 μPa)

According to the basic criteria of C-A difference levels, the results are the following:

a) Lower HVAC immission noise → dBC-dBA = 56.6 - 46.7 = 9.9 dB

b) Higher HVAC immission noise → dBC-dBA = 59.4 - 50.6 = 8.8 dB

As one can see, in both cases the C-A difference is lower than 10 dB. It is important to note that the dBA does not ‘communicate’ the high level of energy in infrasound and low-frequency areas, and the tonal components is characteristics of the sound under analysis.

10.2. Case 2: Coworking open plan offices

At the top floor of a new building, a company decides to offer places for a Coworking labor environment, because they wanted to give a view of the Lima city through the glass façade. They did not realize that the electrical sub-station and all the electromechanical installations are above of that space, however, on a precast reinforced concrete slab. People were developing strong headaches, mental distractions and discomfort because of the steady low-level of humming noise. The following graphics show the sound measurement in the middle of the open-plan office, where it is possible to see that the difference between C-A level always is less than 10 dB (Fig. 8-a), and their spectrums have a high sound level in 125 Hz and strong energy in middle frequencies (Fig. 8-b).

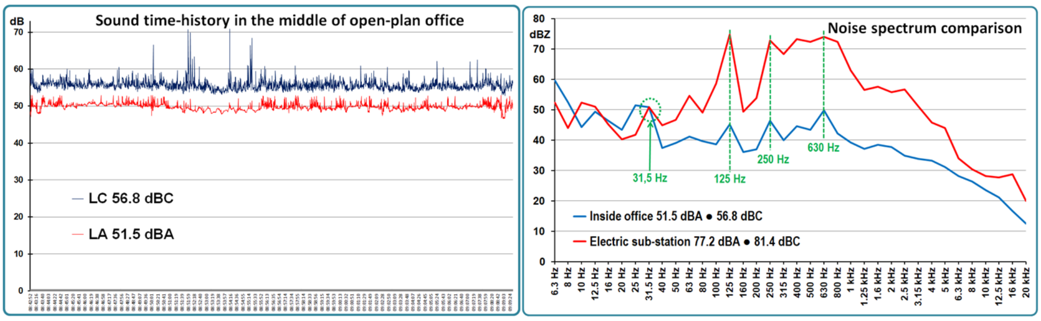


Fig. 8. Sound pressure level inside an open plan office (re dB 20 μPa)

According to the basic criteria of C-A difference levels, the results are the following:

a) Noise immission in open-plan offices → dBC-dBA = 56.8 – 51.1 = 5.3 dB

b) Noise emission in electrical room → dBC-dBA = 81.4 – 77.2 = 4.2 dB

As one can see, in both cases, the C-A difference is lower than 10 dB. It is important to note that the dBA does not ‘communicate’ the tonal components characteristics of the sound under analysis.

Fig. 9. Pictures taken in the places where the measurements were done (Case #1)

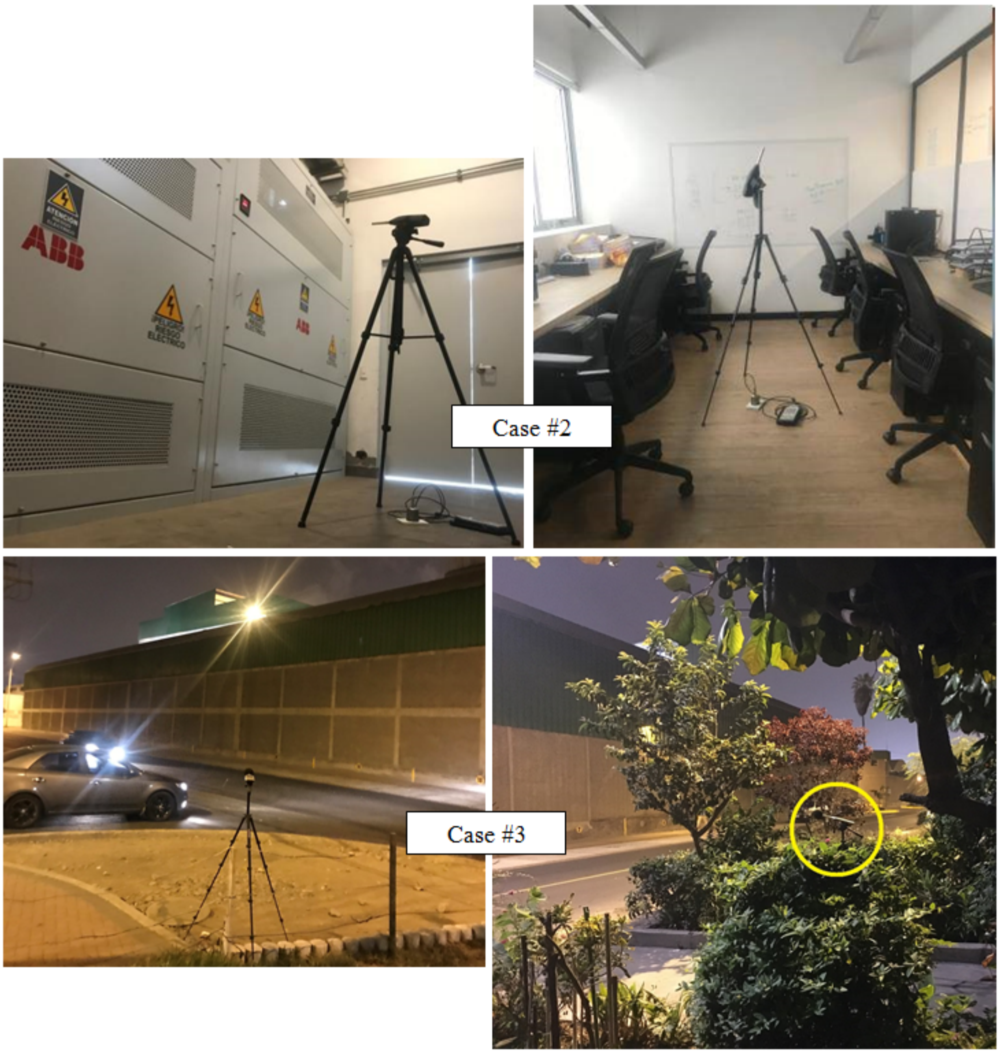


Fig. 9. Pictures taken in the places where the measurements were done (Case #2, Case #3)

10.3. Case 3: Immision noise in outdoor areas from a paper mill industry

The criterion for applying the C-A value is not only useful for indoor measurements but also for outdoor measurements. It is important in these cases to eliminate the unwanted sound from vehicles passing by; the author proposes one method to determinate the *Specific Sound* of one particular noise source from the *Total Sound* measurement, published in this Journal in December 2018 [35].

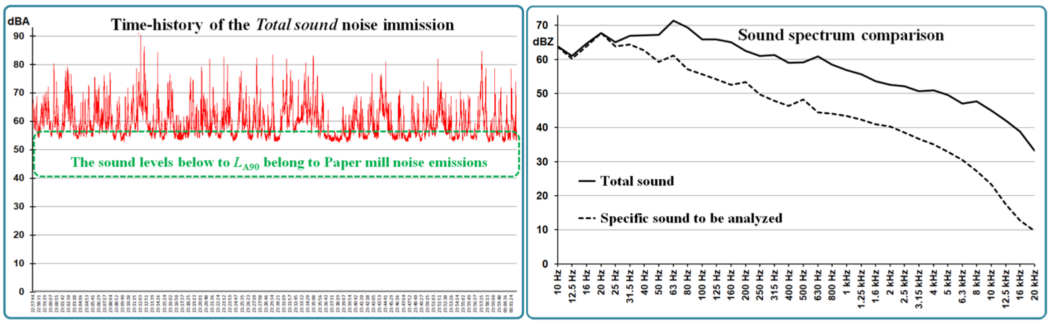


Fig. 10. Outdoor noise level from a paper mill industry (re dB 20 μPa)

In Fig. 10-a one can see the time-history of the *Total Sound* of one measurement, but for the analysis the *Specific Sound* level was used and its sound spectrum is in Fig. 10-b.

11. Rating dBC-dBA measurements using the whole bandwidth

In order to take into account the possible LFN annoyance when a dBA measurement is conducted, the first work that suggests adding a 'penalty' for these characteristics. Published in 1994 by Lambert & Valet *'Study related to the preparation of a communication on a future EC Noise Policy,'* they proposed tentatively that when the average difference between dBC and dBA is 10 dB or more, a penalty should be added for a L_{eq} of less than 60 dBA [30]. They talked of using dBC minus dBA, so it is necessary to consider the whole frequency bandwidth; there are no further clarifications or explanations.

Canada has some industrial noise regulations based on similar criterion (Quebec, Alberta), a few municipalities in Spain, one Ordinance in Lima (Peru), and a couple Australian cities. Also, it is being discussed to incorporate it into an Argentinian Standard.

But what about when the dBC-dBA difference gives a small value less than 10 dB? There are many situations where this is possible just when the dBA level is high, usually when the measurement point is close to the noise source. In these cases, it is possible to get wrong judgments, because the $L_C - L_A$ value is lower than 10 dB, and because the sound level in dBA units does not 'communicate' the strong energy in the low-frequency region (like in Case #1) and is useless with high tonal sound levels (like in Case #2).

12. Rating dBC-dBA measurements using the low-frequency bandwidth

WHO in [30] also suggests *'since a large proportion of low frequency components in the noise may increase annoyance considerably, they should be assessed with appropriate octave or 1/3 octave instruments.'* For the measurements that were made to this Paper it used C-A in a low-frequency region (as it is recommended in the Draft of German DIN 45680:2013 [36]), it means to calculate $L_C - L_A$ just using the equivalent continuous sound pressure level (ECSPL) but, for this Paper, it had been used the results of the averaging C-weighted and A-weighted from 16 Hz to 200 Hz (identified as dBC_{LF} and dBA_{LF} respectively), according to ISO 1996 Third Edition *'low-frequency sound'* definition [37].

In Table 1 the equivalent sound levels in 1/3rd octave band of the two measurements inside Hospital's intermediate recuperation room are presented, in order to calculate its ECSPL in a low-frequency bandwidth.

Table 1
Case #1: Calculation of ECSPL in low-frequency bands in intermediate recuperation room

16 Hz	20 Hz	25 Hz	31,5 Hz	40 Hz	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz	(re dB 20 μPa)	
50.9	53.3	49.6	52.8	52.5	48.5	51	44.9	41.2	39.2	39.6	40.2	**Sound measured** L_Z	
42.4	47.1	45.2	49.8	50.5	47.2	50.2	44.4	40.9	39.0	39.5	40.2	57.3	$L_{C_{eq},T}$ (dBC_{LF})
-5.8	2.8	4.9	13.4	17.9	18.3	24.8	22.4	22.1	23.1	26.2	29.3	33.6	$L_{A_{eq},T}$ (dBA_{LF})

Table 1 (Continuation)

16 Hz	20 Hz	25 Hz	31,5 Hz	40 Hz	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz	(re dB 20 μPa)	
58.3	57.7	50.6	51.8	51.3	48.4	51	42.3	42.3	42.5	40.1	43.3	**Sound measured** L_Z	
49.8	51.5	46.2	48.8	49.3	47.1	50.2	41.8	42.0	42.3	40.0	43.3	58.3	$L_{C_{eq},T}$ (dBC_{LF})
1.6	7.2	5.9	12.4	16.7	18.2	24.8	19.8	23.2	26.4	26.7	32.4	35.3	$L_{A_{eq},T}$ (dBA_{LF})

In Table 2 the equivalent sound levels in 1/3rd octave band of the measurement in the middle of the open-plan office is presented, in order to calculate its ECSPL in low-frequency bandwidth.

Table 2
Case #2: Calculation of ECSPL in low-frequency bands in open-plan office

16 Hz	20 Hz	25 Hz	31,5 Hz	40 Hz	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz	(re dB 20 μPa)	
67.9	64.6	64.3	64.2	68.8	67.2	70.1	66.1	62.1	68.7	58.0	57.4	**Sound measured** L_Z	
59.4	58.4	59.9	61.2	66.8	65.9	69.3	65.6	61.8	68.5	57.9	57.4	75.4	$L_{C_{eq},T}$ (dBC_{LF})
11.2	14.1	19.6	24.8	34.2	37.0	43.9	43.6	43.0	52.6	44.6	46.5	55.2	$L_{A_{eq},T}$ (dBA_{LF})

In Table 3, on the other hand, the differences between those values are calculated, and as one can see, the differences are always greater than 10 dB.

Table 3
Case #2: Calculation of ECSPL in low-frequency bands in open-plan office

Location	$L_{C_{eq},T}$ (dBC_{LF})	$L_{A_{eq},T}$ (dBA_{LF})	$dBC_{LF}-dBA_{LF}$	**Difference**
Case #1: Lower HVAC immision noise	57.3	33.6	23.7	>10
Case #1: Higher HVAC immision noise	58.3	35.3	23.0	>10
Case #2: Open-plan office	75.4	55.2	20.2	>10

13. Relationship between '$L_C - L_A$ using the whole bandwidth' and 'dBC-dBA using the low-frequency bandwidth'

It is important to note in a simple way (see Table 4) how different the results of these two low-frequency sound descriptors are, because in some particular cases:

a) The $L_C - L_A$ value (using the whole bandwidth) is less than 10 dB and this criterion does not express objectively the low-frequency content.

b) The $L_C - L_A$ value (using the whole bandwidth) is less than 20 dB and this criterion does not express objectively the high low-frequency content.

The author presented at ICSV 26^{th} a Paper with an exhaustive analysis [38], for the present article some of those data is shared, and enhanced with new ones:

Table 4
Comparison among different measurements $L_C - L_A$ and $dBC_{LF} - dBA_{LF}$ (re dB 20 μPa)

Location	**Whole bandwidth**			**Third band 16 Hz to 200 Hz**		
	dBC	dBA	$L_C - L_A$	dBC_{LF}	dBA_{LF}	$dBC_{LF} - dBA_{LF}$
Steel casting control site Point #1	81.1	72.7	5.2	80.4	60.1	20.3
Steel casting control site Point #2	83.1	77.9	2.9	81.2	61.1	20.1
Steel casting control site Point #3	88.7	85.0	3.3	85.8	65.8	20.0
Case #1: Lower HVAC noise	56.6	46.7	9.9	57.3	33.6	23.7
Case #1: Higher HVAC noise	59.4	50.6	8.8	58.3	35.3	23.0
Case #2: Open-plan office	56.8	51.5	5.3	75.4	55.2	20.2
Dwelling impacted by pump noise	62.6	55.3	7.3	58.6	42.9	15.7
Tech office inside a factory #1	67.6	53.0	14.6	67.5	41.7	25.8
Tech office inside a factory #2	67.6	51.7	15.9	67.4	41.6	25.8
Tech office inside a factory #3	67.6	51.6	16.0	67.3	41.5	25.8
Tech office inside a factory #4	67.6	51.4	16.2	67.5	41.7	25.7
Tech office inside a factory #5	67.2	50.1	17.1	67.2	41.5	25.8
Case #3. Point #1 day hour	71.7	56.3	15.4	71.8	50.1	21.7
Case #3. Point #2 day hour	70.5	55.8	14.7	70.7	46	24.7
Case #3. Point #3 day hour	72.4	58.6	13.8	72.5	50.4	22.1
Case #3. Point #1 night hour	69.1	53.4	15.7	69.2	46.5	22.7
Case #3. Point #2 night hour	73.0	53.8	19.2	73	52.4	20.6
Case #3. Point #3 night hour	69.9	56.1	13.8	69.7	47.7	22.0
Office #1 impacted by traffic noise	67.4	56.9	10.5	66.8	45.2	21.6
Office #2 impacted by traffic noise	67.2	56.2	11.0	66.5	45.2	21.3
Office #3 impacted by traffic noise	69.6	58.2	11.4	69.3	48.2	21.1
Dwelling #1 close to cooling towers	53.9	43.7	10.2	52.9	34.7	18.2
Dwelling #2 close to cooling towers	57.8	45.7	12.1	57.1	34.4	22.7
Dwelling #3 close to cooling towers	61.8	48.1	13.7	61.4	39.2	22.2
Mechanical adjustment control point	69.6	60.7	8.9	68.4	49.4	19.0
Electrical adjustment control point	82.8	77.2	5.6	80.2	61.4	18.8
Quality control point	87.4	78.1	9.3	86.4	67.3	19.1
Elemental school classroom	71.9	60.4	11.5	72.1	53.2	18.9
Kinder school classroom	60.7	46.1	14.6	60.9	38.5	22.4
Pre-kinder school classroom	68.1	55.2	12.9	68.3	48.6	19.7
School playground	66.4	56.1	10.3	68.7	45	23.7
Music classroom close to HVAC	63.1	59.2	3.9	60.2	43.3	16.9

Some legal references point out that an LFN condition may exist when the time-weighted average $L_C - L_A$ (using the whole bandwidth) is equal to or greater than 20 dB, but as it can observe in the above table that it is not completely true, it means that the C-A value using the whole bandwidth does not have robustness.

For this article the author presents some results, but clarifies that he found out the same behavior in 85 different cases in the sense of the direct C-A value was less than 14 dB and on the contrary, their $dBC_{LF} - dBA_{LF}$ was greater than 15 dB or even greater than 20 dB.

14. Standards and national references to prognosis or forecast the LFN

Some countries have their own legislation about LFN assessment, such as: Poland (10 to 250 Hz), Germany (8 to 125 Hz), Sweden (31.5 to 200 Hz), Denmark (10 to 160 Hz), Finland (20 to 200 Hz), The Netherlands (10 to 200 Hz), Japan (10 to 80 Hz), Great Britain (10 to 160 Hz), Russia, Spain, etc., and it is very difficult to correlate the researches from those countries, because their references values are quite different from each other.

The ANSI/ASA S12.9 Part 4:2005 (R2015) in its Annex D *'Sounds with strong low-frequency content,'* presents a descriptor based on the time-mean-square sound pressures in the 16, 31.5 and 63-Hz octave bands, so the corresponding low-frequency sound pressure level is symbolized by LLF; this descriptor should be applied only for strong low-frequency content and when C-A is greater than 10 dB, but this Annex is just 'informative', it is not mandatory its use or application.

The idea of using just the spectrum of inferior frequencies bands to analyze the LFN was born in Germany: *'In German-speaking countries can refer to the field tests by Wietlake and Kubicek. This was the basis for the first draft of DIN 45680 standard for the years 1990 to 1992 on determination and assessment of low-frequency noise emissions.'* [39]. This Standard was the first to introduce the C-A method, but using the results of the averaging C-weighted and A-weighted from 8 Hz to 100 Hz, was published in 1997. Even though the last version of DIN 45680 recommends the use of C-A but it does not consider frequencies above 125 Hz [36].

It could be interesting of having one single Standardized low-frequency sound descriptor like $dBC_{LF} - dBA_{LF}$, the one is presented in this Article.

15. Defining a specific sound descriptor to assess the LFN: $dBC_{LF} - dBA_{LF}$

The ISO 1996 Third Edition does not propose as mandatory any 'correction' or 'adjustment' for sound with strong low-frequency content [37] compared with the previous ones; because of this the author believes that it is important to have an International standardized sound descriptor for low-frequency assessment. The ILFN annoyance is not just a problem inside dwellings but is also important at workplaces when a mental work is needed not just in offices but in control production points in noisy areas. Because the time-weighted average $L_C - L_A$ using the whole bandwidth *'will give a crude information about the contribution of low frequency sounds'* [30], it is not recommended to use this parameter.

Conclusions

Over the past 50 years, plenty of information about the ILFN impact on people's health exists, but legislation is not always mandatory to make a right assessment for low-frequency content. Mostly it is just when its presence is suspected or if it is proven to exist.

After more than 80 years, it is time to 'retire' the A-weighting frequency for measuring sounds with complex spectrum or tonal components, and even more to consider that it does not express the low-frequency content in noise. Throughout the life of the dBA, many acousticians have been warning that its use does not consider the real impact of low-frequencies, and the A-weighting curve lacks validity especially at frequencies below 250 Hz, because its noise level is underestimated.

'A-weighting is largely derived from studies of human listeners utilizing tonal signals and likely does not fully capture the relationship between complex signals and perceived loudness.

It does not account for the frequency spectra of signals and likely underestimates contributions of complex signals across the frequency range of hearing.' [18]

Prediction parameter for LFN annoyance assessment

In order to suggest a single parameter to assess the LFN, under the concepts of International Standard ISO 1996, the author proposes using the difference between $dBC_{LF} - dBA_{LF}$, because if the low-frequency components are a concern (at workplaces or housing) the reference threshold value should be equal to or greater than 15 dB; so, in this way with the averaging of 1/3rd octave band from 16 Hz to 200 Hz (the standardized ISO low-frequency range), the uncertainties because of the energy in middle or high frequencies are discarded. For this calculation is possible to write simple software and should be considered as a tool to improve the sound analysis that contains tonal or high levels of low-frequency noise.

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