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POSSIBLE REPRESENTATIVE INDOOR ACOUSTIC ENVIRONMENT SPECTRA

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ABSTRACT

The goal of this investigation is to evaluate the possibility of defining an alternative indoor sound spectrum based on objective and verifiable data, representative for an average household in Europe. Such an alternative indoor sound spectrum could then be used to evaluate airborne sound transmission performance.
Different noise subcategories of commonly found sound sources in residential buildings are proposed, and a corresponding representative noise spectrum is given for each noise category. The effect of considering time filtering (Slow and Fast) in the analysis of the sound source time signals and in the determination of the maximum noise spectrum is investigated.
Then, alternative indoor sound spectra are obtained based on the emission spectra of the considered sound sources subcategories, each being weighted by its estimated occurrence time. The comparison of the different alternative indoor spectra obtained is discussed.
Furthermore, three main sound sources categories are also investigated.

Keywords: *building acoustics, indoor noise, acoustic rating, sound transmission.*

1. INTRODUCTION

Currently, the protection against airborne sound transmission between two rooms is evaluated through a single number quantity (SNQ) composed of the weighted sound level difference or the sound transmission index, to which is added a spectrum adaptation term C; indeed, a total of 4 adaptation terms is defined in ISO 717-1 [1]. The calculation procedure is based on the use of A-weighted pink noise as a reference sound source. The choice of pink noise to represent the current acoustic environment in buildings is not clearly justified in the standard. However, it is the result of its 1996 revision merging the German rating-curve method with the French source-spectrum method (pink noise from 100 to 5000 Hz).
The rapid growth of the lightweight residential buildings based on walls and floors including many cavities associated to relatively limited acoustic performance in the low frequency range has led to question regarding occupant's comfort.
Growing questions have also been raised, regarding the low frequency noise of modern service equipment, household appliances and audio-visual devices, in particular [2].
However, it should be mentioned that acoustic comfort investigations in residential buildings, especially timber based, have not demonstrated major complaints relative to indoor sound transmission in France and in Sweden but rather problems relative to impact noise [3-4] and outdoor noise transmission [4].
Unlike other requirements related to fire integrity or structural strength, the link between sound sources and their effects on people, such as annoyance, is not as straightforward. Indeed, it is commonly accepted that a bridge for example has to be designed and dimensioned taking into account the heaviest rolling vehicles allowed for traffic with a security margin. However, this is not applicable for acoustic annoyance. Regarding acoustics, loud music can ultimately be less annoying than the sound of a child crying, a dog barking or neighbors talking. This is precisely because the occurrence, the time of the event are also important, so that it seems rather important to have a statistical representation of sound sources in dwellings in order to determine an indoor noise spectrum. The frequency aspect is also of importance since building separating

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components have to be selected to attenuate most of these sound sources to reduce annoyance as broadly as possible.
Today the most dramatic events related to acoustics are more often linked to the repeated noises from neighbor voices and behavior, rather than music played during an evening gathering, which happens less frequently and is usually regulated and punished (night-time noise disturbance).
An investigation was dedicated to the influence response to noise in large houses converted into flats in the UK [5]. Impact noise was found to be the dominant component of noise from the flat above. Nevertheless, subjective ratings of noise disturbance were analyzed in relation to the household activities and physical properties of flats. They were found to be affected by different sorts of domestic appliance, such as kitchen equipment, television, radio and hi-fi unit, leading to the idea of using the number of events and realistic noise spectra for building acoustic performance evaluation.
This paper is an extension of a short communication published in 2022 [6] proposing a new indoor sound spectrum based on objective and verifiable data, representative for an average household in Europe. It was obtained from the energetic sum of the emission spectra of sound sources commonly found in residential buildings, each weighted by its estimated occurrence time. This work was part of a broader study aiming at proposing new sound insulation descriptors. The proposed indoor sound spectrum was used to define alternative SNQ. Their perceptual relevance was then assessed by means of loudness calculations. The main results of this study can be found in [7].
Different noise subcategories of commonly found sound sources in residential buildings are reviewed, and a corresponding representative noise spectrum is given for three main noise categories. Compared to [6], more noise source types are included such a social gathering noise, pets noise and a broader selection of music sounds. The effect of considering time filtering (Slow and Fast) in the analysis of the sound source time signals and in the determination of the associated noise spectrum is investigated.
Then, alternative indoor sound spectra are obtained based on the emission spectra of the considered sound sources subcategories, each being weighted by its estimated occurrence time. The comparison of the different alternative indoor spectra obtained is discussed.
Finally, three different sound sources categories based on the investigated subcategories are then investigated.

2. INDOOR NOISE SOURCES

Since air-borne sound transmission is to be investigated, sources of pure structure-borne sound (e.g., footsteps, slamming doors, moving furniture) are not considered in this work. Furthermore, sources that are not considered as part of the normal use of dwellings, such as smoke detector alarm, do-it-yourself tools (drill, electric saw, etc.) were also discarded.
A non-exhaustive list of possible sources of indoor noise was created subjectively, yielding a list of more than 100 sources of noise ordered according to three main categories:

- Household sound sources: house appliances (refrigerator, vacuum cleaner, etc.), building service equipment (plumbing noise, AC and ventilation units, etc.);
- Living creatures sound sources: human voices, social gatherings, pets;
- Sound reproduction sources: TV, HiFi sound systems, music of different styles.

2.1 Indoor noise sources representativeness

In order to select a representative set of indoor noise sources, the following approach was used [6].
The method is based on statistical data provided by Eurostat [8]. Note that no work was found in the acoustic literature on the use of such data to deduce statistical information on the percentage of occurrence of indoor noise types. It appears however as a valuable source to estimate the average occurrence of indoor noise in dwellings. This data gives the amount of daily time spent on average for a set of activities in 21 European countries. By weighting the amount of time by the population in each country, a daily time spent estimate is obtained for each activity, averaged across Europe.
The next step is to use this data to estimate the time spent for each source of the subjective list. The difficulty is that the Eurostat categories are generally too broad to differentiate between individual source types. Television data is an exception. For this source type, the Eurostat time spent gives a statistically valid number of daily hours. For most of the other sources, assumptions must be made as to their relative running time. To take advantage of the statistical data provided by Eurostat, similar categories of sources are considered in order to reduce the number of relevant sources from the subjective list. A total of 20 source subcategories are selected at the end of this process. They are listed in Table 1.

Table 1. Relative importance and associated parameters for the selected indoor sound source subcategories.

Sound source subcategory	$R_{participation,EU}$ (%)		T_{daily} (hrs)		Depends on nb occupants (yes/no)		$T_{avg,weekly}$ (hrs)	K_i
	Value	Origin	Value	Origin	Value	Origin		
Mechanical ventilation	70	[11]	24.00	assum.	no	assum.	117.60	1.0000
Refrigerator/freezer	99	[12]	12.00	assum.	no	assum.	83.16	0.7071
Daily grooming (excl. WC)	100	[8]	1.09	[8]	yes	assum.	17.47	0.1486
Cooking appliances	65	[8]	1.08	[8]	yes	assum.	16.11	0.1370
Video equipment (excl. games)	82	[8]	2.53	[8]	no	assum.	14.43	0.1227
Meals	99	[8]	1.82	[8]	no	assum.	12.56	0.1068
Dishwasher (excl. load/unload)	58.4	[10]	2.00	assum.	no	assum.	8.18	0.0695
House cleaning appliances	41	[8]	1.07	[8]	yes	assum.	7.11	0.0605
Dish hand wash and handle	40	[8]	0.75	[8]	yes	assum.	4.82	0.0410
Washing machine, no spin	96	[10]	0.50	assum.	no	assum.	3.36	0.0286
Washing machine, spin cycle	96	[10]	0.17	assum.	no	assum.	1.12	0.0095
Children voices	28.8	[9]	0.50	assum.	no	assum.	1.01	0.0086
Video games	4	[8]	1.30	[8]	no	assum.	0.39	0.0033
Audio equipment	6	[8]	0.95	[8]	no	assum.	0.38	0.0032
Toilet flush	100	assum.	0.02	assum.	yes	assum.	0.27	0.0023
Phone/doorbell ring	100	assum.	0.02	assum.	no	assum.	0.12	0.0010
Social Gatherings	25	[8]	0.38	[8]	no	assum.	0.67	0.0057
Pets	7	[8]	0.50	assum	no	assum.	0.25	0.0021
Shouting/fighting	10	Assum.	0.25	assum	no	assum.	0.18	0.0015
Music	6	[8]	0.95	[8]	no	assum.	0.38	0.0032

To estimate the importance of a source, an importance indicator is defined for each sound source subcategory, based on its occurrence, as described below. Subcategories with a high importance value indicator are more likely to contribute to the indoor noise. When the occurrence time for the i^{th} subcategory can be considered as independent from the number of occupants in the dwelling or room (e.g., refrigerator, ventilation), an average weekly occurrence indicator $T_{avg,weekly,i}$ is calculated as:

$$T_{avg,weekly,i} = R_{participation,EU,i} \times T_{daily,i} \times 7 \quad (1)$$

where $R_{participation,EU,i}$ is the participation rate, i.e., the estimated share (in %) of European dwellings where the considered source subcategory is present or the share of the population who reports engaging in the considered activity on a regular basis, and $T_{daily,i}$ is the average daily occurrence time (in hours).

One difficulty with this method is to correctly take into account sound sources for which the occurrence time depends on the number of occupants (e.g., daily grooming). For such sources, the average daily occurrence time corresponds to the usage time by one occupant. Therefore, the weekly occurrence indicator is calculated based on the following expression:

$$T_{avg,weekly,i} = R_{participation,EU,i} \times T_{daily,i} \times 7 \times N_{avgHousehold,EU} \quad (2)$$

where $N_{avgHousehold,EU}$ is the average household size in Europe, estimated to 2.3 members [8].

Once the weekly occurrence indicator is determined for all considered sound sources, the values are normalized as follows to obtain the relative importance indicator K_i:

$$K_i = T_{avg,weekly,i}/max(T_{avg,weekly}) \quad (3)$$

The relative importance indicator is estimated for the 20 source subcategories listed in Table 1 by order of decreasing importance. The origin of the parameter values considered in the calculation is specified in order to provide an indication of their reliability (pure assumptions being referred to as “assum.”).
In Table 1, the subcategories marked in light blue fall into the “Household sound sources” category, those in light orange into the “Sound reproduction sources” category, and those in light green into the “Living creatures sound sources” category. The last four subcategories have been added, compared to work presented in [6]. For social gatherings, a number of 20 different recordings for different situations has been used. The pets subcategory includes dog playing and running, a dog barking and well as a cat mewing. The music subcategory is composed of two types of hard rock music, a rock piece, a jazz piece, a pop piece, and an easy guitar piece.

3. SPECTRAL CHARATERISTICS OF INDOOR SOURCES

3.1 Method

Each source category listed in Table 1 is qualified in terms of emission levels. A typical indoor noise spectrum can then be obtained as the sum of the emission levels weighted by the values of the relative importance indicator.
Calibrated audio recordings were made in two different dwellings, using a SQobold portable measuring system from HEAD Acoustics and a Brüel & Kjær Type 4966 microphone. Recordings of social gathering were performed in different situations.
In order to obtain a spectral representation in one-third octave bands between 50 and 5000 Hz, either the percentile index L_{10}, i.e., the level exceeded 10% of the time, or the maximum level L_{max} are considered. To evaluate these two types of indicators, the “Slow” or “Fast” time filtering was applied to the recordings. Note than in the results previously presented in [5], the index L_{10} was obtained from a 1 s linear averaging.
The sound power level is then obtained in each third octave band, considering both direct and reverberant sound fields, using the following expression:

$$L_{W,10/\max} = L_{10/\max} - 10\lg\left(\frac{Q}{4\pi d^2} + \frac{4}{A}\right) \quad (4)$$

where d is the distance from the considered source to the microphone (comprised between 1 and 3 m), Q is the source directivity factor and A is the total sound absorption area of the room (in m²), estimated from the room dimensions and typical sound reverberation time values. The directivity factor is determined based on assumptions for each sound source and considered always equal or higher than 2. However, it should be emphasized that this parameter has little influence as the reverberant sound field is dominant. Finally, the spectral values that are lower than the background noise level + 6 dB were excluded from the analysis.
Note that this approach was chosen because it is simple and allows for an important number of in-situ characterizations. However, this can come at the expense of accuracy and the resulting sound power spectra may differ from data measured in acoustic laboratories.
For each source subcategory, the measured spectra are combined following two separate methods:

- Calculation of an energetic average of the different spectra (hereafter referred to as “AVG” spectrum);
- Selection of the maximum value at each one-third octave band (hereafter referred to as “MAX” spectrum).

The AVG and MAX spectra are then smoothed by applying a running average on 3 consecutive one-third octave bands to attenuate strong spectral variations due to one individual source. This is performed on the L_{10} evaluated spectra and also on the L_{max} spectra with the Slow and Fast time filtering.
It should be noted that this approach does not consider the occurrence time of each individual sound source in the subcategory. Therefore, the AVG and MAX spectra are strongly dependent on the available data and cannot be considered statistically valid.
The equivalent indoor sound spectrum is obtained from the characteristics (relative occurrence and emission spectrum) of the sound source categories presented in Table 1 as:

$$L_{W,indoor,j} = 10\lg\left(\sum_{i=1}^{N} K_i \times 10^{L_{W,i,j}/10}\right) \quad (5)$$

where N=20 is the number of sound source subcategories, K_i is the relative importance factor of the i^{th} category and $L_{W,i,j}$ is the estimated sound power level of the i^{th} subcategory for frequency band j.
The same principle is also applied to obtain sound power spectra associated to each of the three chosen categories.

3.2 Subcategories spectra

As an example, the spectrum for the different subcategories and the associated equivalent indoor noise spectrum (labelled as “TOTAL”) are shown in Figure 1.
As shown in Figure 1(a), the indoor sound spectrum derived from the AVG spectra has less low-frequency content than the pink noise spectrum currently considered in ISO 717-1 [1] and is rather flat above 500 Hz.

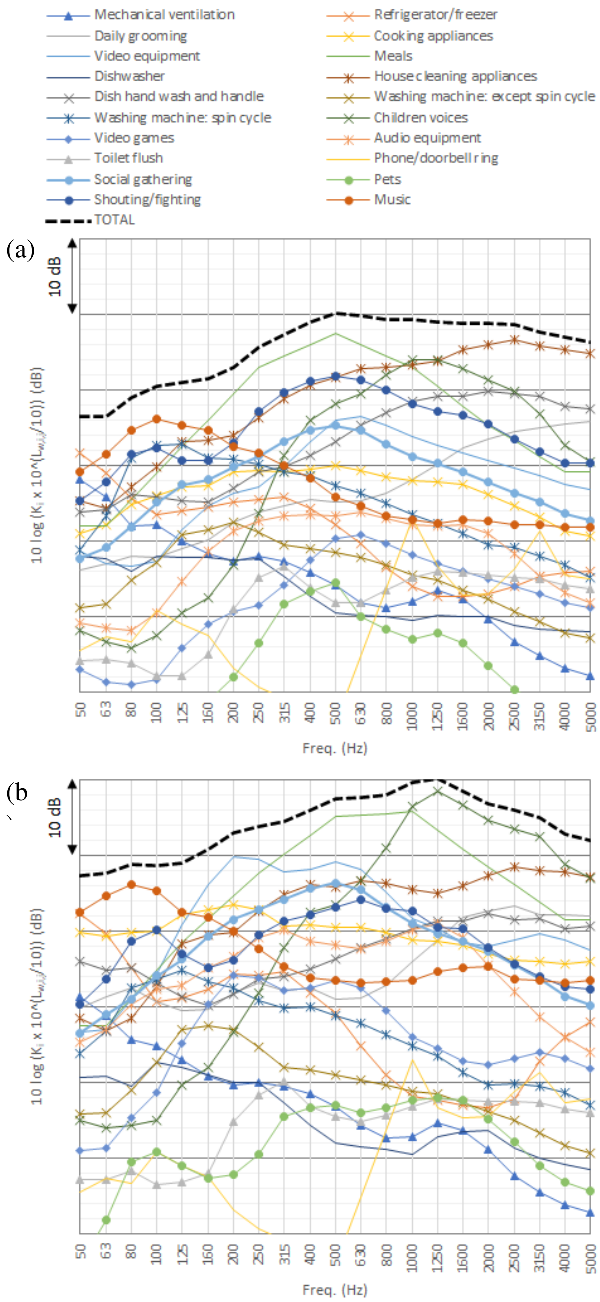

Figure 1. Indoor sound spectrum derived from (a) the AVG spectra and (b) the MAX spectra, of the considered sound source subcategories based on L_{10} spectra using slow time filtering.

However, the AVG spectra proposed for each category are strongly dependent on the quantity and quality of the available data. Given the small number of recordings and the simplifications made to derive the sound power level of each recording, it should be considered that these AVG spectra are subject to significant uncertainties.

The indoor sound spectrum derived from the MAX spectra, see Figure 1(b), is also different from pink noise, with less low-frequency content but also less energy in the high frequency range. The MAX spectra of each category are associated to similar uncertainty levels as the AVG spectra. Thus, these results should be considered with care.

Figure 2 compares the different equivalent indoor noise spectra obtained from the different indices (L_{10}, L_{max}, Slow, Fast). It can be seen that the different spectra have a similar shape with frequency, independently of the use of the indices; only the combination between the different sources for each subcategory matters (averaging or max).

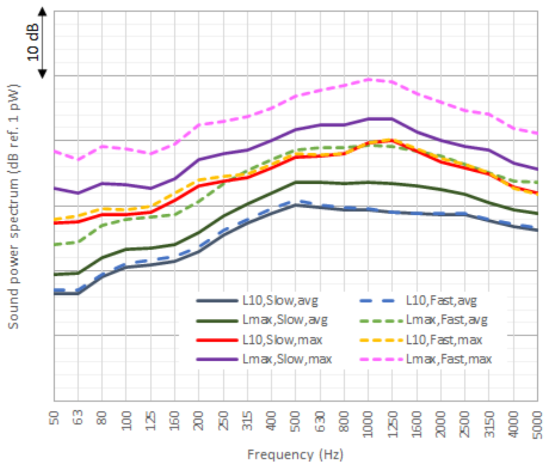

Figure 2. Indoor sound spectra derived of all considered sound source subcategories.

This is made obvious in Figure 3 where the same spectra are reported but normalized to the same value at 1 kHz for those using averaging and those using a maximum approach. Figure 3 also presents the corresponding idealized spectra that could be used for SNQ calculation, as well as those obtained in [6]. Using the averaging approach (AVG), the idealized spectrum obtained with more sound sources in the present work is very similar to the one obtained in [6], with a positive slope of 1.5 dB per one-third octave between 50 and 500 Hz, then a constant value. Using the maximum approach (MAX), the idealized spectrum obtained is slightly different from the one obtained in [6]; however, the spectra show a positive slope with increasing frequency in the low frequency range. It should be noted that a pink noise spectrum in one-third octave band would correspond to a constant value.

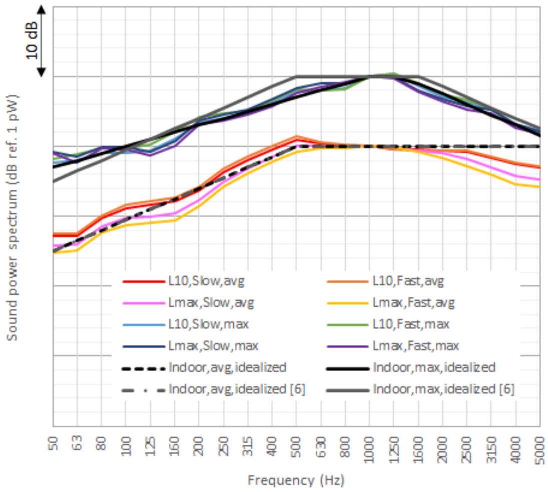

Figure 3. Possible alternative indoor sound spectra derived of all considered sound source subcategories.

3.3 Categories spectra

It is also of interest to deduct an alternative indoor spectrum for the three different categories selected.

Figures 4 to 6 shows the different results respectively for the "Household sound sources" category, the "Living creatures sound sources" category and the "Sound reproduction sources" category.

It can be seen that these three categories present different behaviors with frequencies. The averaging approach for the "Household sound sources" category leads to an idealized indoor sound spectrum close to the one obtained considering all subcategory sources. Using the maximum approach, the idealized indoor sound spectrum for the "Household sound sources" category could be different from the one obtained considering all subcategory sources.

Similar remarks could be made for the "Living creatures sound sources" category.

Indeed, major differences are observed for the "Sound reproduction sources" category. In this case, the idealized indoor sound spectrum is quite different from the one obtained considering all subcategory sources. However, it should be emphasized that such idealized indoor sound spectrum for the "Sound reproduction sources" category, highly depends on the type of music chosen as sources. Thus, these results should be taken with care. Nevertheless, for this "Sound reproduction sources" category, a pink noise could also be a candidate as idealized indoor sound spectrum.

It should be added that when applying no weighting to the subcategories composing a category, the results are not largely modified for the "Household sound sources" category and the "Living creatures sound sources" (not shown in the paper). This does not hold for the "Sound reproduction sources" category as shown in Figure 7.

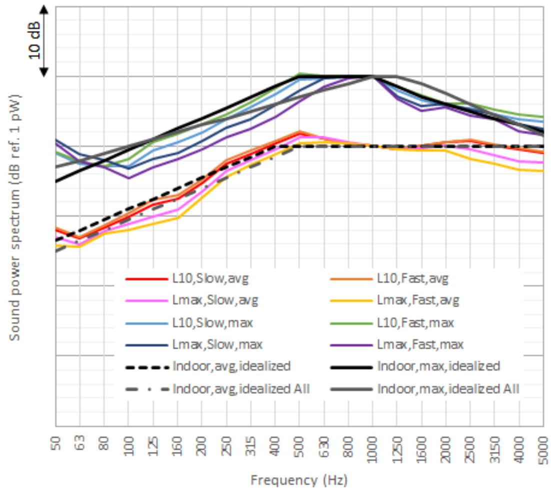

Figure 4. Possible alternative indoor sound spectra derived for "Household sound sources" category.

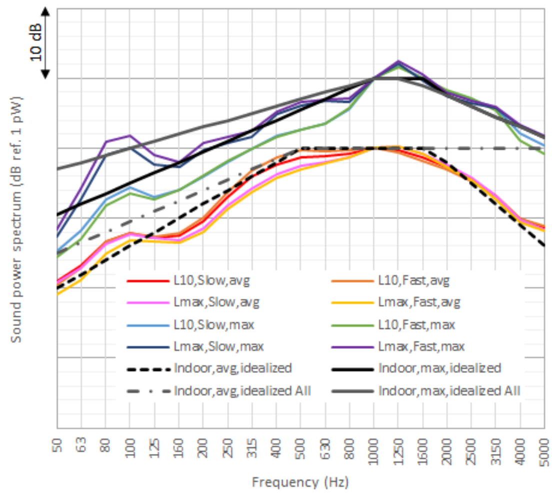

Figure 5. Possible alternative indoor sound spectra derived for "Living creatures sound sources" category.

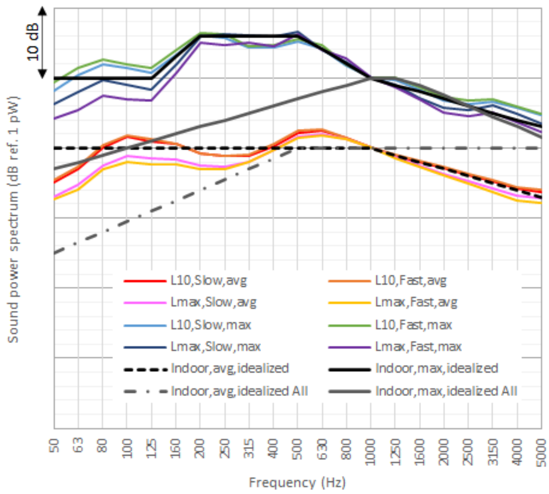

Figure 6. Possible alternative indoor sound spectra derived for "Sound reproduction sources" category.

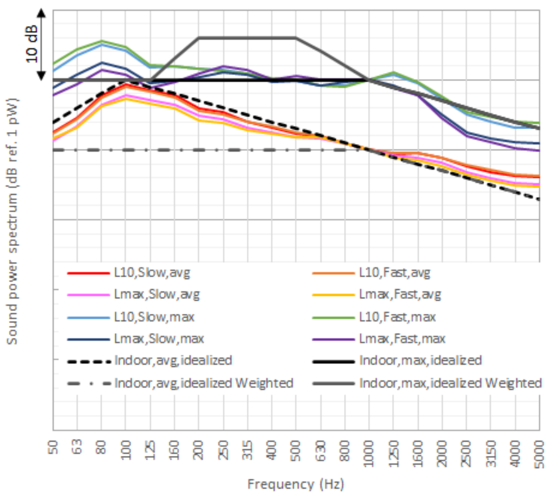

Figure 7. Possible alternative indoor sound spectra derived for "Sound reproduction sources" category without weighting contributing subcategories.

4. CONCLUSION

This paper presents an extension of a previous study [6] concerning a proposal for indoor sound spectrum based on sound sources found in residential buildings. The background data and the different calculation steps leading to the evaluation of such indoor sound spectrum proposals have been presented. It should be stressed that this definition of an indoor sound spectrum only relies on occurrence, and does not consider reported, subjective annoyance or disturbance of the involved sounds or sound sources. Indeed, this definition is questionable since disturbance is more generally associated to a specific annoying event rather than a weighted by occurrence multi sound sources noise level. Furthermore, many assumptions were necessary to determine the relative importance of the considered sound sources based on occurrence. Indeed, it is difficult to consider all possible relevant sound sources; for example, musical instruments that could have a strong influence on the indoor acoustic environment have not been considered as yet.

Some might argue that such a statistically based approach on sound sources in dwellings is a wrong philosophy, explaining the necessity to design dwellings not on a statistical behavior and usage of the occupant but rather on the worst case scenario. It is understandable that from a structural point of view, a building has to be constructed based on very strict rules, i.e., the possible worst situation, so the building does not crumble. However, regarding acoustics, it is questionable that the worst situation has to be taken into account, since occupant behavior is at stake, especially looking at indoor airborne sound insulation. It is believed that quite loud noise from neighbors, out of a statistical social standard conduct, will fall into housing-related anti-social behavior. This type of problem does not have to be considered when designing dwellings indoor airborne sound insulation. Anyway, the analysis without weighting contributing subcategories, i.e., removing the statical aspects regarding the different sound sources, was indeed also explored in this work.

When considering all sound sources subcategories, the obtained idealized indoor noise spectra have less energy at low frequencies than the pink noise used in the current standard [1]. Even if more sound sources and more subcategories have been considered in this paper, the obtained idealized indoor noise spectra are in close agreement with those from [6]. The use of the two indices L_{10} and L_{max}, and of the Slow and Fast time filtering was not associated to major differences in the obtained results. The approach of averaging the sound sources spectrum in each subcategory or of taking the maximum spectrum level has more influence on the evaluated results.

For the "Household sound sources" and the "Living creatures sound sources" categories, the deduced idealized indoor sound spectra were not different in behavior from those deduced considering all sound sources subcategories. This was however not the case for the "Sound reproduction sources" category. Due to the choice of music pieces selected for sound sources, the results can indeed vary. For this "Sound reproduction sources" category, a pink noise could be a candidate as idealized indoor sound spectrum. The effect of sound reproduction system types used to listen to music remains to be investigated on the indoor sound spectrum for "Sound reproduction sources" category. Indeed, Bluetooth small size speakers have become quite popular and are generally limited in low frequency rendering.

In order to improve the confidence level of these results, long-term acoustic monitoring in a statistically representative number of dwellings or other building types could be planned; although it could be expected that this solution including monitoring and data analyzing might be particularly costly. Moreover, acceptance by building occupants might be a practical difficulty, in a context of growing concerns about privacy. To evaluate the perceptual relevance of the proposed indoor sound spectra, psycho-acoustic experiments by means of laboratory listening tests, could be deployed. However, such experiments have been criticized since they were often based on an evaluation of the perceived annoyance or disturbance, assessed from a limited number of participants under laboratory conditions with a limited variety of sound stimuli imposed by listening test duration. Due to the requirement of a sufficiently large statistically representative set of tested walls/floors and of a large number of test persons, proper assessment of SNQs by listening tests is indeed very time consuming. In order to overcome this, the replacement of the subjective listening test-based evaluation of loudness, by calculated Zwicker's loudness has been introduced as an alternative methodology [13]. Therefore, the perceptual relevance of the proposed indoor sound spectra will be in the near future assessed by means of loudness calculations as presented in [7].

5. ACKNOWLEDGMENTS

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