# STANDARD DEVIATIONS IN FIELD MEASUREMENTS OF IMPACT SOUND INSULATION

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## ABSTRACT

Sound insulation of buildings has traditionally been measured at 1/3-octave center frequency bands from 100 Hz to 3150 Hz. The measured frequency range was originally chosen to begin at 100 Hz because of assumed increasing measurement uncertainty at lower frequencies. In impact sound insulation, however, the lower frequencies affect the subjective evaluation of floors much. Standards ISO 140 and 717 defining the measurement methods were revised during the 1990's, and measurements at enlarged frequency range including center frequency bands 50 Hz, 63 Hz and 80 Hz became possible. The standards do not define the measurement uncertainty at the three low frequency bands. The object of this article is to define standard deviations of impact sound pressure levels and reverberation times at the enlarged frequency range. Impact sound insulation of 50 concrete floors has been measured in field. Comparisons between measured standard deviations and theoretical results have been made. 50 Hz, 63 Hz and 80 Hz do not deviate much from results at range from 100 Hz to 160 Hz. Hence, if measurements below 100 Hz were considered questionable, higher frequency bands to band 160 Hz could also be put under question. Frequency range below which standard deviations begin to increase corresponds well to Schroeder's cut-off frequency. Measured standard deviations are slightly greater than calculated theoretical values, which is probably due to field conditions in which the structures can never be perfect.

## 1. INTRODUCTION

Impact sound insulation of buildings has traditionally been evaluated at 1/3-octave bands from 100 Hz to 3150 Hz. Importance of lower frequency bands, however, has been known since long [1-6]. Actual sound pressure levels from real footsteps are often highest at frequencies below 100 Hz. Thus, taking these sound levels into account in objective measurements with tapping machine has lead to better correlations between objective measurements and people's subjective evaluation of floors [7-11].

Method for evaluation of impact sound insulation is defined in standards ISO 140 and 717. Measurement result has usually been expressed as weighted normalized impact sound pressure level denoted in field measurements as $L'_{n,w}$. Even though earlier research had recommended to enlarge the measured frequency range down to the centre frequency band of 50 Hz, this was not done because of assumed increasing uncertainty of measurements [1, 12]. In the latest revision during the 1990's, standards finally gave possibilities to evaluate the frequency range below 100 Hz, when a new evaluation method, spectrum adaptation terms $C_I$ for frequency range 100-2500 Hz and $C_{I,50-2500}$ Hz for range 50-2500 Hz, was presented [13-15].

Measurements of building acoustical quantities are based on the assumption of diffuse sound field. Standard ISO 140-7 states that in low frequency bands below 400 Hz and especially below 100 Hz no diffuse field conditions can be achieved in small rooms [14]. However, the revised standards do not define the uncertainty of measured single-number quantities including low frequency bands 50, 63 and 80 Hz. Standard ISO 140-2 [16] defines the acceptable repeatability and reproducibility values for measurement results at each centre frequency band, but these values are given only for frequency bands above 100 Hz. Because there is no exact knowledge about measurement uncertainty at lower frequencies, some countries, e.g. Finland, have not adopted the spectrum adaptation terms in their national building regulation [17].

Before the revision of standards ISO 140 and 717 defining the measurement methods for evaluation of airborne and impact sound insulation, the standard deviations of impact sound pressure levels and reverberation times were studied in the Nordic countries [18-19]. These results were partly achieved in laboratory conditions and amount of field measurements was limited. The object of this article is to define standard deviations of impact sound pressure levels and reverberation times at the enlarged frequency range in field measurements.

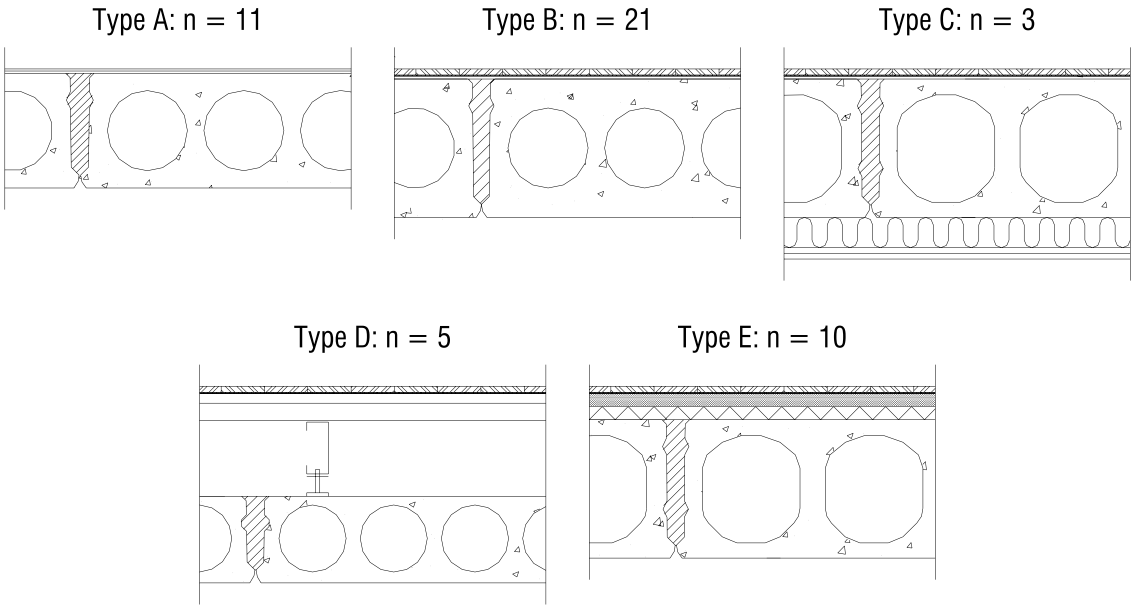
## 2. MEASUREMENTS

### 2.1. Collection of data

In this research, only concrete floors of new multi-storey residential buildings have been measured. All measurements have been carried out in pre-cast concrete buildings which are the most usual multi-storey building type in Finland. These buildings have load-bearing concrete elements as separating walls and concrete sandwich panels as outer walls. Non-bearing separating walls in the residences are mostly light-weight floors with timber or steel frame. Bearing structures of intermediate floors are hollow core slab fields or cast concrete slabs.

Measured floors include all typical Finnish floor structures of new buildings. The measured floors have been dealt into five groups on the basis of floor covering as follows (figure 1):

- floor type A: floor covering cushion vinyl, n = 11
- floor type B: floor covering multi-layer parquet with soft underlayment, n = 21
- floor type C: floor type B with suspended ceiling, n = 3
- floor type D: raised floor system, n = 5
- floor type E: floating floor, n = 10



Type A: n = 11

Type B: n = 21

Type C: n = 3

Type D: n = 5

Type E: n = 10

*Figure 1. The measured concrete floor types.*

Within each floor type, there is variation in e.g. the bearing structure which can be hollow core slab or cast concrete slab; the mass of the slab varies, too. Detailed information of the sections and structural layers of measured floors is given in reference [20]. Weighted reduction of impact sound pressure level $\Delta L_{\mathrm{w}}$ of floor coverings is shown. For cushion vinyls, $\Delta L_{\mathrm{w}}$ is 17 or 19 dB. For multi-layer parquet lying on soft underlayment, $\Delta L_{\mathrm{w}}$ is 18 or 19 dB. Raised floor system allows for assembly of HVAC installations above the bearing structure. The bearing structure of raised floor consists of steel or timber spacers supporting a board structure on which the floor covering is installed. Dynamic stiffness *s'* of the resilient layer of floating floors varies from 8 to 20 MN/m$^3$.

All measurements described in this research have been carried out in unfurnished rooms. The volume of the rooms varies between 24 and 117 m$^3$. The amount of measured floor structures is 50. Most of the rooms were small: 32 measurements were done in rooms having a volume smaller than 40 m$^3$. The floors concerned have been measured during years 1999-2003. Measurement results for this presentation have been chosen so that they fulfill the Finnish impact sound insulation requirements, i.e. weighted normalized impact sound pressure level $L'_{\mathrm{n,w}}$ is not more than 53 dB.

## 2.2. Measurement methods

Impact sound pressure levels are measured according to standard ISO 140-7 [14]. Four tapping machine and four microphone positions have been used. In spatial averaging of impact sound pressure levels, twelve excitations are included so that the spatial average is a combination of four microphone and four tapping machine positions. Averaging time for a measurement of single tapping machine excitation has been 10 s.

Reverberation time measurements have been carried out according to standards ISO 140-7 [14] and ISO 354 [21]. Decay of 40 dB has been measured. Reverberation time T60 is obtained by multiplying the measured value of T40 by 1,5. Two loudspeaker positions have been used. The loudspeaker has been placed in the corner of the room. Number of microphone positions has been four. In each position, two decays have been measured. The average of reverberation time is calculated from twelve decays so that they are combined from two loudspeaker positions and four microphone positions. The equipment used in sound pressures level and reverberation times corresponds to requirements of accuracy class 1.

# 3. ANALYSIS AND RESULTS

## 3.1. Impact sound pressure levels

Standard deviation $s_{\mathrm{p}}$ for mean square pressure $p^2/p^2_0$ ($p_0 = 2 \times 10^{-5}$ Pa) is calculated from impact sound pressure levels $L_{\mathrm{j}}$ and spatial average $L_{\mathrm{i}}$ of levels $L_{\mathrm{j}}$ as

$$s_{\mathrm{p}} = \sqrt{\frac{1}{n-1}\sum_{\mathrm{j}=1}^{12}\left(10^{L_{\mathrm{j}}/10} - 10^{L_{\mathrm{i}}/10}\right)^2} \tag{1}$$

For convenience, standard deviation of sound pressure $s_{\mathrm{p}}$ is given in decibels as sound pressure levels. Approximation $s_{\mathrm{L}}$ for standard deviation $s_{\mathrm{p}}$ can be derived from standard deviation of mean square pressure relative to mean square pressure as [22]

$$s_{\mathrm{L}} = 4{,}34\frac{s_{\mathrm{p}}}{10^{L_{\mathrm{i}}/10}} \tag{2}$$

Standard deviations of all 50 measurements are collected in figure 2. Each point in figure 2 represents standard deviation of a single measurement at a certain frequency. The figure shows also the limit below which 90 % of the measured standard deviations lie.

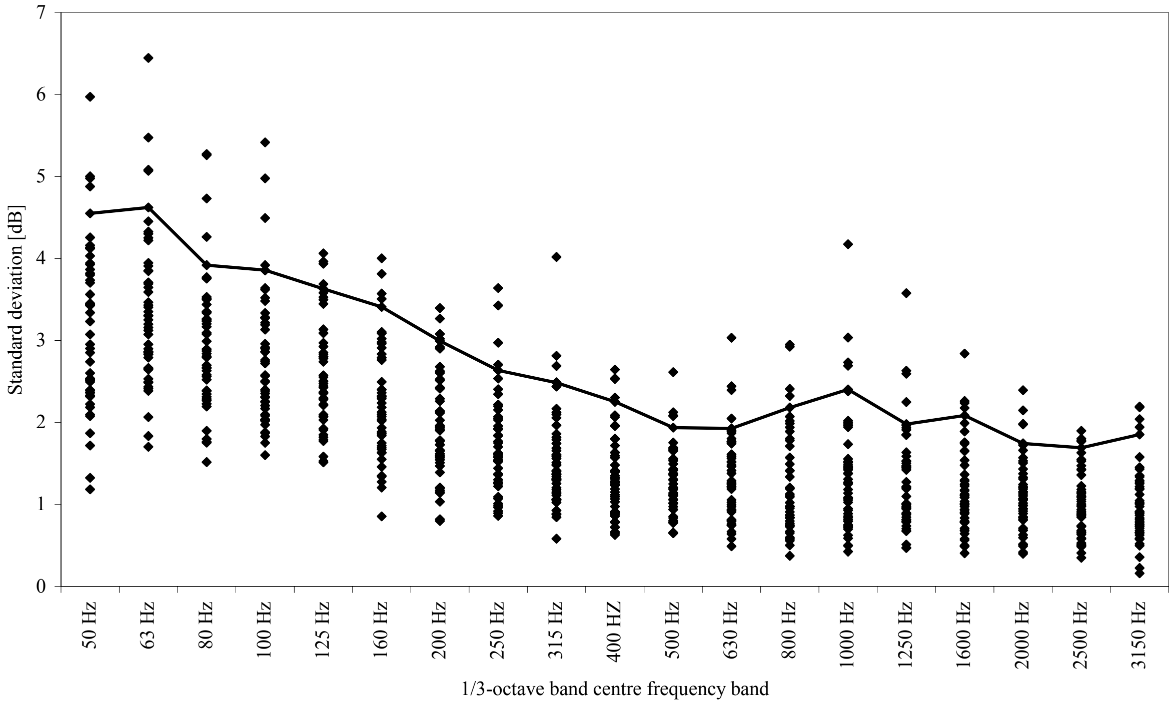


*Figure 2. Standard deviations of impact sound pressure levels in all 50 measurements. Continuous line shows the limit below which 90 % of the standard deviations lie.*

The measured standard deviation tends to increase as frequency band is decreased. However, at the lowest frequency band of 50 Hz, the deviation varies from around 1 dB to around 6 dB. Hence, at the lowest bands, the deviation is not in all cases necessarily greater than at high frequencies, but it can be also lower. The 90 % limit is around 4,5 dB at frequency bands of 50 and 63 Hz. At bands of 80, 100, 125 and 160Hz, the limit is between 3,5 and 4 dB. At higher frequencies, the limit decreases and lies around 2 dB at frequency bands above 400 Hz. Difference between largest and smallest deviation is also at its lowest at high frequencies.

## 3.2. Reverberation times

Standard deviation $s_\mathrm{T}$ for reverberation time $T_{60}$ is calculated from single measurements $T_{60,\mathrm{i}}$ as

$$s_\mathrm{T} = \sqrt{\frac{1}{n-1}\sum_{\mathrm{j}=1}^{12}\left(T_{60,\mathrm{i}} - T_{60}\right)^2} \tag{3}$$

Standard deviations for all 50 measured floor structures are given for 1/3-centre frequency bands from 50 Hz to 3150 Hz in figure 3. Figure 3 shows also the limit below which 90 % of the measured standard deviations lie. As like as standard deviations of impact sound pressure levels, the measured standard deviations of reverberation times tend to increase as frequency band is decreased. Below 250 Hz, nevertheless, the 90 % limit changes irregularly so that deviations at frequency band of 80 Hz are lower than deviations at 50, 63, 100 and 125 Hz. At frequency band of 400 Hz and at higher frequencies, the 90 % limit of standard deviations is below 0,15 s. The limit is decreasing even at the highest frequency bands which tendency is not as clear in the deviations of impact sound pressure levels in figure 2. In some cases, the standard deviations at low frequencies, can be as low as at the highest frequencies. The difference between largest and lowest deviation is at centre frequency of 125 Hz and at lower bands.

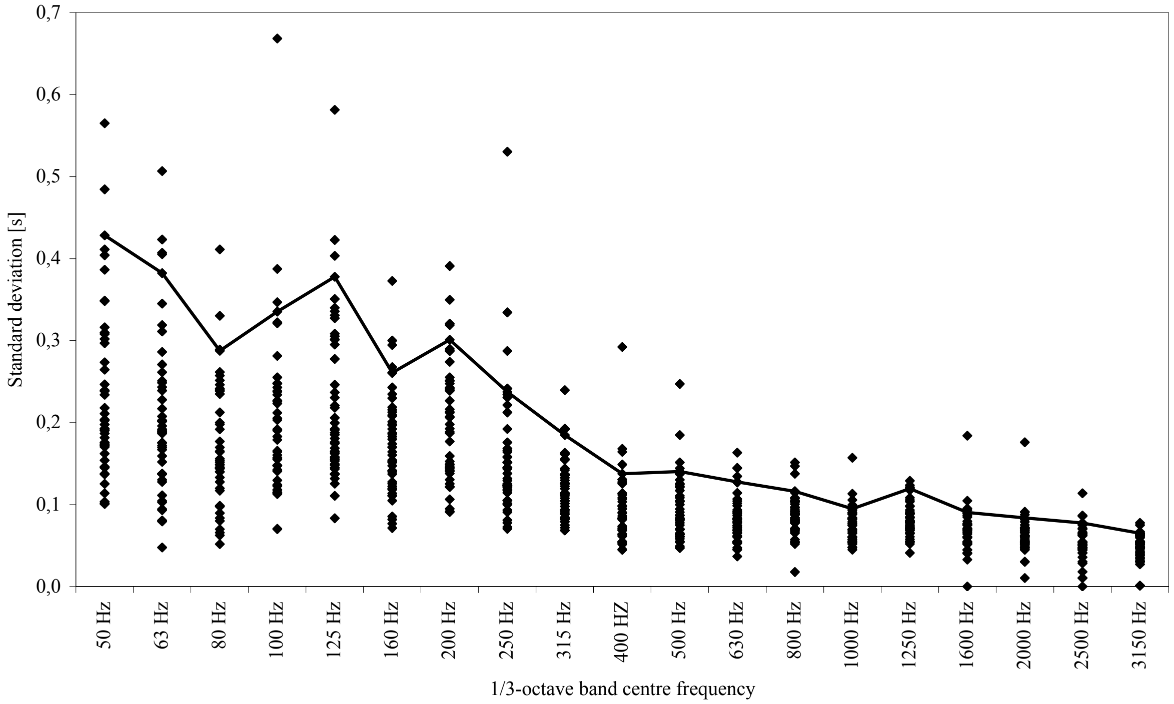


*Figure 3. Standard deviations of reverberation times in all 50 measurements. Continuous line shows the limit below which 90 % of the standard deviations lie.*

## 4. COMPARISONS WITH THEORY AND DISCUSSION

Knowledge of statistical properties of sound field in closed room is based much on work done by Schroeder. In 1954, Schroeder derived a critical frequency $f_s$ which represents the limit between the frequency range with well separated and strongly overlapping resonances [23]. This is usually considered as the limit of diffuse and non-diffuse sound field. This frequency was later corrected by Schroeder and Kutruff [24] as

$$f_s = 2000\sqrt{\frac{T_{60}}{V}} \tag{13}$$

This frequency corresponds to the situation where the number of overlapping normal modes is three. In a typical unfurnished room having a volume of 30 m3 and reverberation time $T_{60}$ of 1,5 s, critical frequency is about 450 Hz.

From figures 2 and 3 can be seen that there is not very large difference in measured standard deviations of impact sound pressure levels or reverberation times at frequency range below 160 Hz. Figures 2 and 3 also show that in the measurements, critical frequency $f_s$ lies at the frequency range below which standard deviations of both impact sound pressure levels and reverberation times begin to increase. If larger standard deviations of impact sound pressure levels than 2 dB are not desirable, the measured frequency range should be limited to begin at around 400 Hz in field measurements. Hence, larger standard deviations have to be accepted while the most important frequency range from people’s subjective point of view lies at more than one octave lower range.

Standard deviations of reverberation times tend to decrease slightly even at the high frequencies above 500 Hz. In standard deviations of impact sound pressure levels, such tendency cannot be noticed. This difference could be explained by the assumption that reverberation time measurements depend more on the characteristics of sound field than measurements of impact sound pressure levels which are affected by structural factors. E.g. following irregularities in structures may cause such increase in standard deviations of impact sound pressure levels: cushion vinyl is unproperly glued; bond between leveling compound under the floor covering and bearing structure has disappeared; parquet is in contact with wall or HVAC installations; there is small cracks or holes in the structures which cause airborne sound leaks between source and receiving rooms. These irregularities increase the impact sound pressure levels usually at high frequencies. Accuracy of measurement devices cannot explain the standard deviations which are always greater than precision of sound level meter.

Rooms where measurements were carried out were mainly small, most of them having a volume of less than 40 m$^3$. Theoretically, the standard deviations should decrease when room volume increases. Such decrease cannot, however, be clearly noticed [20]. This can be partly explained by the structural reasons in field conditions. However, despite the increase in room volume, the height of the room rarely becomes greater. In Finland, typical room height is around 2,6 m. Even though there is not much measurement results of rooms having a volume greater than 70 m$^3$, the room height can partly explain the standard deviations measured in large rooms.

Olesen [18] has given some results from field measurements. In these measurements, number of tapping machine positions has been four or five and averaging time 16 s or 32 s. While rotating microphone in one position has been used, the standard deviations are mainly caused by tapping machine positions. For concrete floors, standard deviations vary between 0,5 dB at high frequencies and 5 dB at lower region. Standard deviations of 4 dB have been measured at the highest frequency bands, too. Measurement results shown in figure 2 are at same range as results given by Olesen except that standard deviations defined in this study are mainly below 2 dB at high frequency range.

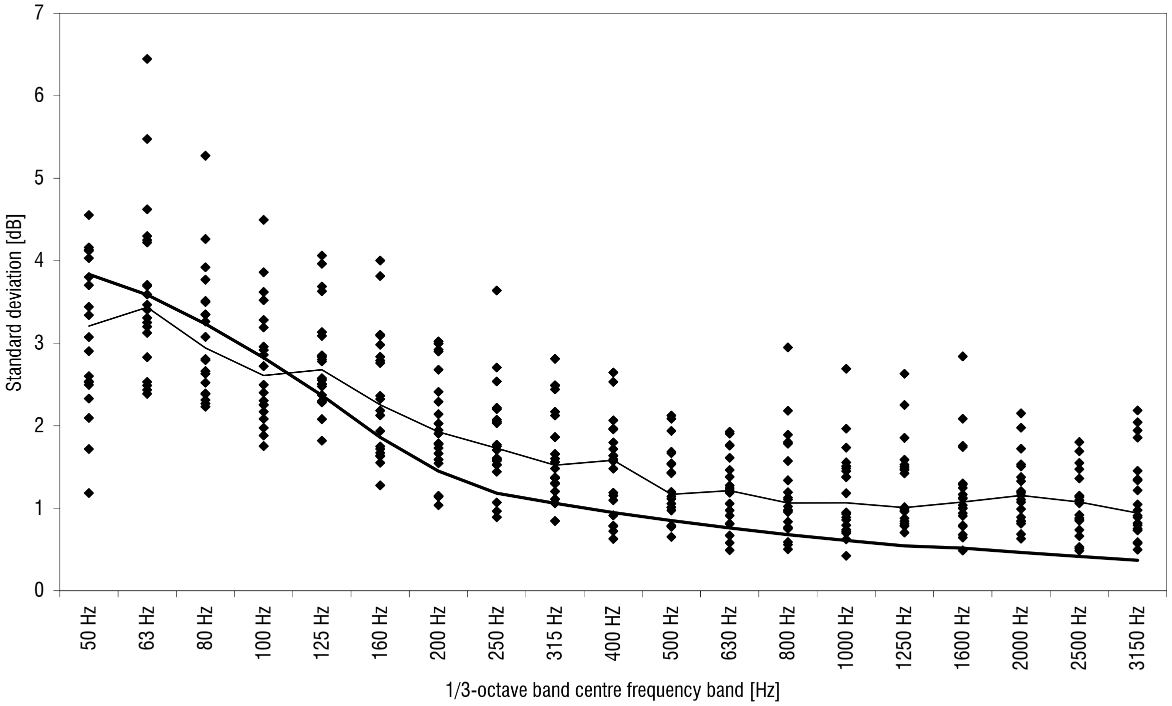


*Figure 4. Measured standard deviations of impact sound pressure levels compared with theoretical values according to Lubman's theory. Thin continuous line shows the median of the measured standard deviations and thick line the theoretical values.*

Measured standard deviations of impact sound pressure levels have been compared with theory published of Lubman [25]. The theory derives standard deviations from reverberation time, bandwidths and modal density of room. Figure 4 shows theoretical standard deviations in comparison with measured standard deviations in rooms having a volume from 27 $m^3$ to 35 $m^3$. Theoretical values are calculated for a rectangular room having a volume of 30 $m^3$ and a reverberation time of 1,5 s [20]. Below 200 Hz the theoretical values agree quite good with the median of the measured deviations. At high frequencies the measured values are greater than theoretical which can be due to the structural variations discussed above. The estimate of reverberation time in the calculation is neither correct in all bands and all rooms.

## 5. CONCLUSIONS

Standard deviations of measured impact sound pressure levels and reverberation times increase when measured frequency band becomes lower. At the high frequency range, the standard deviations in field measurements do not depend only on properties of sound field, but structural factors affect them, too. In this study, limit below which 90 % of measured standard deviations of impact sound pressure levels at frequency bands of 50, 63 and 80 Hz lie is 4,5 dB which is from around 0 to 1 dB higher than 90 % limit for standard deviations at frequency bands of 100, 125 and 160 Hz.

Traditionally, measurements below 100 Hz have been considered too uncertain. Hence, if measurements below 100 Hz were considered questionable because of increasing standard deviation, higher frequency bands from 100 to 160 Hz could also be put under question in field measurements for the same reason as well. Or, if measurements at the frequency range from 100 Hz to 160 Hz are considered to be accurate enough, there is no reasonable cause to put the three lower frequency bands under question.

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