TOWARD A REALISTIC ESTIMATE OF OCTAVE BAND SOUND LEVELS FOR ELECTRIC TRANSFORMERS

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ABSTRACT

The typical starting point, when evaluating the sound emissions of a proposed transformer, is to obtain the manufacturer's sound level data or develop an estimate using generic prediction equations from a published textbook. If sound level information is available from the transformer manufacturer – whether measured or estimated – it is usually given only in terms of an overall A-weighted ("dBA") value. So, for detailed analysis in octave frequency bands, textbook information is still usually required, in terms of the spectral weightings needed to apportion the single dBA level into its component octave band sound levels. Unfortunately, the information in the published reference texts varies enormously with regard to the suggested spectral weighting corrections. The corrections in some texts are internally inconsistent, and the discrepancy among different texts (even those which cite the same primary references) is severe enough to call the whole body of data into question. This paper enumerates the inconsistencies and discrepancies within and among several commonly used acoustical engineering text books and compares the textbook levels to a wide body of data collected at numerous outdoor transformer installations throughout Ontario. Suggestions are provided for realistic spectral weightings and sound level estimates for transformers, on the basis of the measured data.

RÉSUMÉ

Le point de départ typique lors du processus de prédiction des émissions sonores d'un futur transformateur est d'obtenir des données de niveaux sonores du fabricant ou de développer une estimation en utilisant des équations de prédiction génériques à partir d'un manuel publié. Si des données de niveaux sonores sont disponibles auprès du fabricant de transformateur – qu'elle soit mesurées ou estimées – elles le sont généralement seulement en termes de valeurs pondérées selon la courbe A. («dBA»). Ainsi, pour une analyse détaillée par bandes d'octaves, il est habituellement nécessaire de convertir une valeur dBA avec l'aide d'une pondération spectrale suggérée par un manuel publié. Malheureusement, les informations contenues dans les textes de référence publiés varient énormément en ce qui concerne les corrections suggérées pour la pondération spectrale. Les corrections dans certains textes sont en soi incompatibles, et l'écart entre les différents textes (même ceux qui citent les mêmes références primaires) mérite d'appeler l'ensemble des données en question. Ce document énumère les contradictions et les divergences au sein et entre plusieurs manuels d'ingénierie acoustique couramment utilisés et compare les manuels publiés à un vaste ensemble de données de transformateur à ciel ouvert collectées en Ontario. Des suggestions réalistes, basées sur les données mesurées, sont fournies à titre de coefficients spectraux et d'estimations de niveaux sonores pour les transformateurs.

1 INTRODUCTION

In many jurisdictions, sound level limits or acoustic assessment criteria are cited in terms of an overall A-weighted single number sound level – particularly in the case of assessing environmental noise to the outdoors. This type of single number sound level represents a weighted sum of the acoustic energy across the entire audible frequency spectrum, typically from about 20 Hz to about 20 kHz. In general, an A-weighted, summed sound level correlates reasonably well with the perceived loudness of the sound, and therefore also with its potential to cause disturbance or annoyance. For this reason, the overall A-weighted sound level has become the most common descriptor used in assessing environmental noise impact.

But, in the context of predicting sound levels from a planned, new sound source or designing noise control measures, a single-number A-weighted sound level may not suffice, because many of the important factors affecting the propagation of sound are frequency dependent. That is, acoustic mechanisms like shielding by obstacles, attenuation by soft ground, atmospheric absorption and meteorological effects all attenuate high frequency sound to a differing degree than low frequency sound. Therefore, in many cases, the acoustical consultant needs to know the un-summed sound levels of a source across the frequency range of interest – i.e., a set of octave band or 1/3-octave band sound levels.

The modern test standards that provide methods for measuring and quoting the source sound levels of electric transformers [1, 2, 3] include provisions for measuring and publishing octave band, 1/3-octave band and narrowband sound emission levels for transformers. However, the long established and overwhelming norm among transformer manufacturers is to publish only the single-number A-weighted sound level sum.

So, in order to obtain a sound level spectrum, for use in calculating sound propagation, the acoustical consultant typically must resort to using a set of octave band spectral corrections to apportion the A-weighted sum into an estimate of its spectral frequency distribution. Many of the common acoustical textbooks and handbooks provide correction factors for transformers, aimed specifically at deriving an octave band spectrum from a single A-weighted value [4, 5, 6, 7, 8]. To use the corrections, the consultant can simply add (arithmetically) the factor for each octave band to the overall A-weighted sum, resulting in a set of octave band sound levels (typically eight levels).

2 PUBLISHED CORRECTION FACTORS

Table 1 lists the basic octave band correction factors from five published texts and handbooks. We will refer to the basic correction factors as “C1” in counter-distinction to alternative correction factors offered in some of the texts, for special applications (designated herein as “C2” and “C3”).

There are some broad similarities between the various references, insofar as each spectrum of corrections peaks in the 125 Hz octave band, which is to be expected because transformers tend to hum at the first harmonic of the alternating-current line frequency (120 Hz and 60 Hz, respectively in North America). But also apparent from Table 1, and perhaps more important, are the vast differences in the values of the suggested corrections. There is a 20 decibel range at the dominant frequency of 125 Hz, which is distressing to a consultant who needs to make a reasonably accurate estimate of the transformer sound emission spectrum.

Moreover, the alternative factors provided in three of the references increase the spread among the potential schemes. Table 2 summarizes these alternative factors. References [4], [7] and [8] suggest that the basic factor, C1, be used in general applications, while factor C2 should be used in small indoor spaces where standing waves could be present and factor C3 should be used in critical locations where a problem would result if the transformer should become noisier over time.

3 DISCUSSION OF DISCREPANCIES

In considering which, if any, of the published correction spectra is realistic and appropriate to use in an acoustic analysis, we can take note that not all of the schemes are “energy neutral.” That is, if the set of correction values from some of the references is used to apportion the single-number A-weighted sound level sum into its component octave band levels, and those octave band levels are then A-weighted and logarithmically summed, the result differs from the original A-weighted sum. Ideally, there should not be such a difference between the starting and ending A-weighted sum; there should be no acoustic energy gained or lost when breaking a sum into its parts, or adding the parts back together. Table 3 shows the A-weighted residue resulting from the various correction schemes.

Reference [5] is the only one with a zero residue, which means that it is the only scheme that does not increase or decrease the acoustic energy in the octave band spectrum relative to the original A-weighted sound level sum.

If we hypothesize that the intent of some of these correction schemes is not solely to apportion the A-weighted sound level into its component parts, but also to include margins of conservatism or other engineering adjustments (as is discussed by references [4], [7] and [8] in the case of C2 and C3), then it would be reasonable to expect that those schemes would not be energy-neutral – they should tend have a positive residue. The problem is that the C1 and C2 corrections in reference [8] have a negative residue, which would tend to underestimate the sound emissions of the transformer. As well, the C1 schemes proposed by references [4], [7] and [8], which do not purport to include adjustments, do not have zero residues.

Table 1: Published Octave Band Corrections, C1, in Decibels Relative to Overall A-weighted Sum

Frequency [Hz]	Ref [4]	Ref [5]	Ref [6][A]	Ref [7][B]	Ref [8]
31	-1	-3		9	-11
63	5	3		15	-5
125	7	5	17	17	-3
250	2	0	5	12	-8
500	2	0	-4	12	-8
1k	-4	-6	-8	6	-14
2k	-9	-11		1	-19
4k	-14	-16		-4	-24
8k	-21	-23		-11	-31

A. The values in reference [6] are given at the discrete harmonic frequencies of a transformer (multiples of 120 Hz), which fall within the 125, 250, 500 and 1000 Hz full octave bands, respectively.

B. See the Appendix for notes on the factors from reference 7.

On the basis of internal consistency alone, the correction scheme presented in reference [5] appears to be realistic, in that it neither adds energy to nor subtracts energy from the spectrum, relative to the A-weighted sum. However, given the disagreement between the schemes, the use of any one may be suspect, without delving further into their origin. In that regard, Figure 1 reveals an interesting relationship among four of the five references. With the exception of reference [6] the corresponding correction spectra are all exact, scaled images of one another. Or, in other words, they all represent the identical spectral shape, with a frequency-independent constant difference among them. This exact correspondence is too close to be a coincidence, and in fact we will see that it is not a coincidence.

Table 2: Published Alternative Octave Band Corrections C2 and C3, for Use in Special Locations/Applications, in Decibels Relative to Overall A-weighted Sum

Frequency [Hz]	Ref [4]		Ref [7][B]		Ref [8]	
	C2	C3	C2	C3	C2	C3
31	-1	-1	9	9	-11	-11
63	8	8	18	18	-2	-2
125	13	13	23	23	3	3
250	8	12	18	22	-2	2
500	8	12	18	22	-2	2
1k	-1	6	9	16	-11	-4
2k	-9	1	1	11	-19	-9
4k	-14	4	-4	6	-24	-14
8k	-21	-11	-11	-1	-31	-21

B. See the Appendix for notes on the factors from reference 7.

Table 3: A-weighted Residues Resulting from the Application of the Various Correction Schemes and Re-summing Logarithmically

Reference	C1	C2	C3
[4]	2	7	13
[5]	0	--	--
[6]	3	--	--
[7]	12	17	22
[8]	-8	-3	2

None of references [4] through [8] is a primary reference, insofar as presenting direct measurements and analysis of transformer sound levels. Instead, each of those references presents information previously published in other sources. References [4] and [8] cite reference [7] as the source of their data, so we would expect their results all to be identical; indeed, the corrections in [4], [7] and [8] have identical spectral shapes but differ by a significant bias, which remains unexplained. Reference [7] does not cite the origin of its information, although comments in the References section of [8] suggest that [7] was prepared by the firm Bolt, Beranek and Newman ("BBN"). References [5] and [6] quote primary preferences [9] and [10] respectively, as the origin of their information, although [9] and [10] are no longer in print and not readily available. Interestingly, both references [9] and [10] were prepared by BBN. So, it is apparent that all of the correction schemes presented above were derived from information originally compiled by BBN. This common origin explains the common spectral shape among the correction schemes, but does not explain the bias differences or tendency of most of the schemes to add/subtract energy relative to the A-weighted sum.

In an effort to resolve these discrepancies, we attempted to obtain copies of the out of print BBN references, [9] and [10]. Through inter-library loan from the Texas A&M University Library and the Edison Electric Institute Library, respectively, it was possible to obtain a copy of reference [10], published in 1984, and an older version of that same document [11], published in 1978, both of which were prepared for the Edison Electric Institute by BBN. The information presented in references [10] and [11] is identical, and given that reference [11] is the oldest of all of the texts we were able to obtain, it appears to be the closest possible candidate as the origin of the correction schemes presented in the other texts. Unlike the secondary texts, reference [11] explains that the correction factors were derived from a compilation of empirical data gathered from: the available literature, the authors' project files, equipment manufacturers, member companies of the Edison Electric Institute, and site measurements specifically conducted for the preparation of that text.

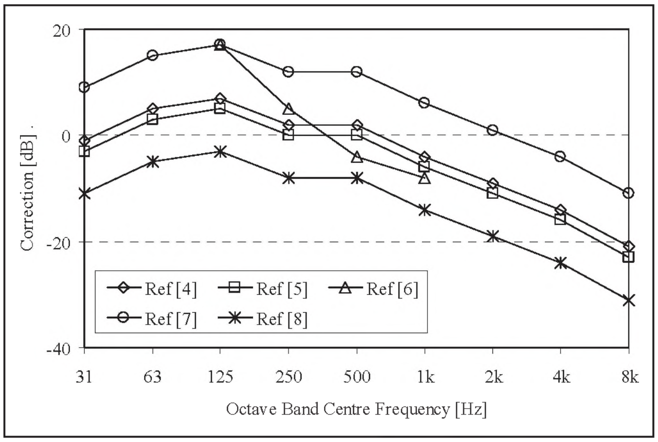

Figure 1: Basic Octave Band Corrections, C1

The correction values in reference [11] are identical to those in reference [5], which is the only set of corrections that does not add/subtract energy from the spectrum, relative to the overall A-weighted sum. Furthermore, reference [11] appears to be either a primary source or very close to a primary source of this information, purportedly based on a compilation of empirical measurement data. Thus, a reasonable conclusion is that the preferred set of correction values is the spectrum published in references [5] and [11].

The corrections from reference [4] are relatively close to the preferred spectrum – greater by just 2 dB in each band. The reason for this 2 dB difference is not known. As discussed further in the Appendix, the large differences of references [7] and [8], relative to the preferred spectrum appear to result simply from errors. References [7] and [8] appear to include conversion errors (between ft^2 to m^2) of 10 dB, which when corrected, results in spectra matching those of reference [4].

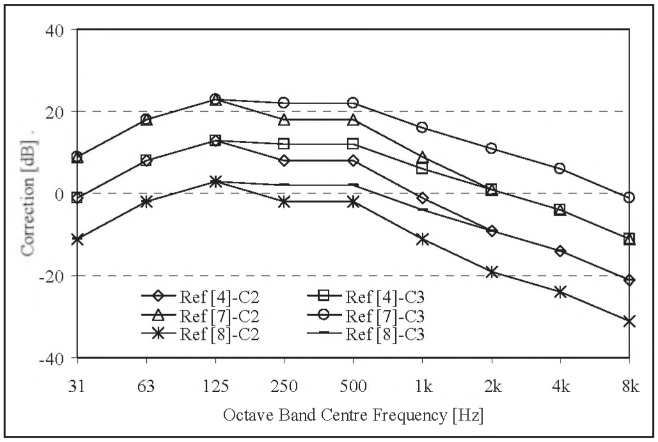

Figure 2: Alternate Octave Band Corrections, C2 & C3

The alternative corrections (C2 and C3) seem dubious, not only because they all add/subtract energy relative to the A-weighted sum, but also because they appear to include adjustments or safety margins that are not explained in the texts and are likely better handled explicitly by the acoustical consultant performing the analysis, based on the situation and his experience and judgment.

4 RECENT MEASUREMENTS

For further evaluation of the published correction factors, or as an alternative to the published data, we have compiled a body of data measured by the authors, involving 36 transformers at 16 different sites throughout the Province of Ontario. The transformers ranged in capacity from 5 Mega-Volt-Amps ("MVA") to 750 MVA. Most of these units were equipped with propeller style cooling fans. Where possible, sound level measurements were conducted with the fans on and off so that the frequency spectra of the transformer core and the cooling fans could be investigated separately. In some cases, the fans could not be turned off, and in such cases the fans were often the dominant source of sound.

The majority of the sound level measurements were conducted using sound intensity instrumentation and methods, generally following the procedures of ISO Standard 9614-2 [12], in order to obtain the best possible rejection of interfering background sound. In some cases, only sound pressure levels were measured, using standard procedures, in which case care was taken to ensure that interference from nearby sound sources was avoided.

In addition to comprising a data set for comparison against the published texts (which were all seemingly derived from the same BBN data set), an ancillary benefit of this new compilation of transformer spectral data is that it presumably represents a more current population of transformers. The previous references were based on transformers measured more than 30 years ago.

The results are summarized in Figures 3, 4 and 5, and in Table 3. The data in Figures 3 and 4 represent the same group of transformers – those for which the fans could be turned on and off, such that separate compilations of spectral weightings could be made. The data in Figure 5 are based on the transformers which could only be measured with the fans operating.

For each transformer, the spectral correction in a given octave band was simply calculated as the arithmetic difference of the octave band sound level minus the overall A-weighted sound level sum. The set of ensemble of corrections in a given octave band across all transformers was then averaged arithmetically, to yield the results in Figures 3 through 5 and Table 3. The data points marked as dots in Figures 3 through 5 are the spectral corrections for individual transformers, while the lines are the ensemble averages.

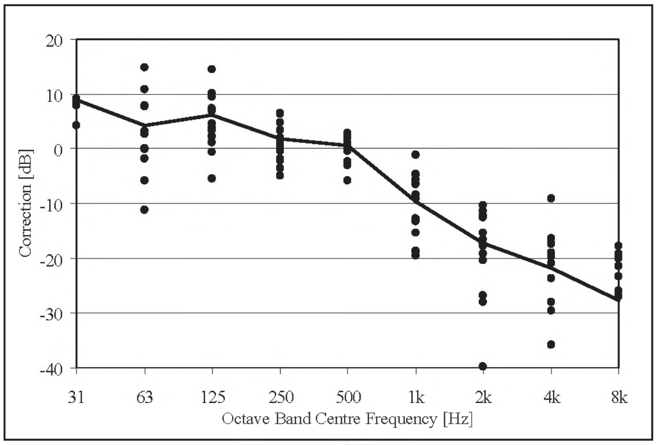

Figure 3: Spectral Corrections from Measurements by HGC Engineering – Transformer Core Only; Fans Off

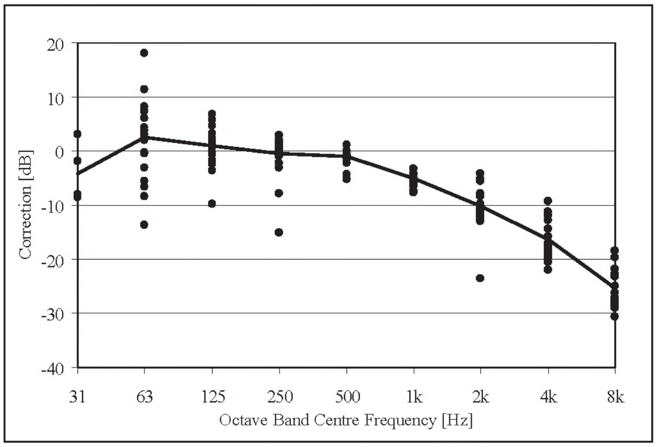

Figure 4: Spectral Corrections from Measurements by HGC Engineering – Fans Only (contribution of core deducted)

The agreement among the three correction spectra listed in Table 3 and the spectrum of the preferred spectrum (reference [11]) is relatively good, as shown in Figure 6. The agreement is particularly good between the two spectra that contain fan sound and that of reference [11]. This result is reasonable, in light of the fact that the measurement data in reference [11] included fan sound.

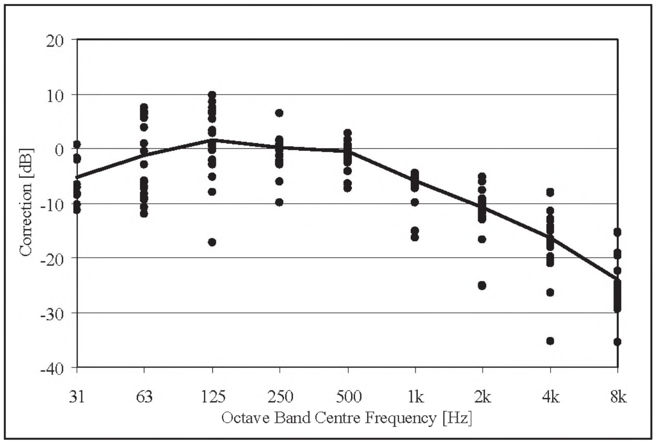

Figure 5: Spectral Corrections from Measurements by HGC Engineering – Transformer Core and Fans Combined

Table 3: Spectral Corrections for Transformers in Decibels Relative to the A-weighted Sum Based on Measurements by HGC Engineering

Frequency [Hz]	Transformer Core Only (Fans Off)	Cooling Fans Only (Core Deducted)	Transformer Core and Fans Combined
31	9	-4	-5
63	4	3	-1
125	6	1	2
250	2	-1	0
500	1	-1	0
1k	-10	-5	-6
2k	-17	-10	-11
4k	-22	-16	-16
8k	-28	-25	-24

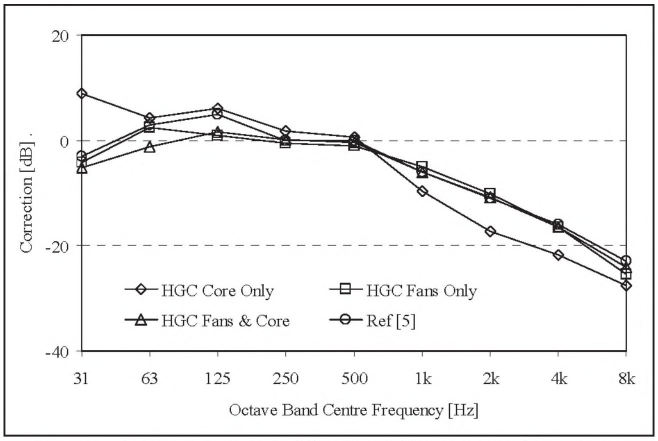

Figure 6: Comparison of Spectral Corrections Based on Measurements by HGC Engineering to Reference [11]

The spectral corrections in the 31 Hz octave band, as shown in Table 3 and Figures 3 through 6 are likely somewhat less reliable than in the other bands, because the majority of measurements included sound levels only from 63 Hz to 8 kHz, meaning that there were fewer data points available in the 31 Hz range. However, this restriction on accuracy may be of minimal consequence because the 31 Hz octave band rarely influences the overall A-weighted sound level significantly for transformers. The value of the A-weighting curve at 31 Hz is -39.4 dB, which de-emphasizes the contribution of the sound in the 31 Hz octave band in the sum.

5 CONCLUSIONS

From a review of several commonly used textbooks and the literature cited by those texts, we conclude that the most reliable published correction spectrum is the one proposed by references [5] and [11] – i.e., the corrections shown in column 3 of Table 1.

Contradictions, errors and unsupported adjustments abound in the published sources, so it is important for the consultant to understand and verify the correction spectrum that is to be used. One way to do so is to ensure that there is no appreciable residual value when re-calculating the A-weighted sum of the apportioned octave band levels, relative to the starting value. Without such a verification, the errors present in some of the texts [7 and 8], could result in octave band levels that are overstated or understated by as much as 10 dB, which is significant.

The new correction factors presented herein do not differ significantly from those of reference [11]. One advantage to the new factors is that separate correction spectra are available for the cooling fans and the transformer core. In many cases, the transformer manufacturer's sound level data will include separate sound levels for the fans and core. So by using the separate correction spectra, the fans and core can be modeled and analyzed individually, which may afford additional accuracy for some projects, particularly those in which the fan noise is dominant.

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APPENDIX

Some explanation of the correction factors from reference [7] are warranted, to avoid a misinterpretation of the manner in which they are presented in this paper. As presented in reference [7] (Table 7-30, page 7-34 of that text), the correction factors appear at first glance to be identical to those presented in reference [4] – i.e., basic correction factor C1 of -1 dB at 31 Hz, +5 dB at 63 Hz, +7 dB at 125 Hz, etc. However, unlike reference [4], reference [7] proposes these correction factors for use in an equation involving US units of measurement, not SI units. Specifically, [7] states the following:

$$L_W = L_{P(NEMA)} + 10\log A + C,$$

where L_W is the octave band sound power level, $L_{P(NEMA)}$ is the overall A-weighted sound pressure level sum measured around the transformer, in accordance with reference [1], A is the area enveloping the transformer *in square feet* and C is the appropriate octave band correction factor.

Because L_W and L_P have reference values in SI units, the use of an area measured in square feet presents a problem, because the authors of reference [7] did not add a unit conversion factor to their equation. The result is that, if the correction factors presented in reference [7] are used with the equation presented in reference [7], the calculated octave band values will be erroneously inflated by an amount equal to ten times the logarithmic ratio of 1 square foot to 1 square meter, which is +10.32 dB. In order to make the octave band correction scheme in reference [7] directly comparable to those of the other texts we adjusted their octave band correction factors to compensate for the error in their equation.

The identification of the unit conversion error in reference [7] is supported by yet another text, reference [13] (also authored by BBN). Reference [13] presents the same equation as reference [7] for deriving the octave band sound power levels from the A-weighted sound pressure level using an area measured in square feet, but reference [13] properly adjusts its spectral correction factors to compensate for the conversion from US to SI units. Thus, for example, the basic correction factors in reference [13] are: -11 dB at 31 Hz, -5 dB at 63 Hz, -3 dB at 125 Hz, etc. These corrections are 10 dB less than those presented in reference [7], which is correct if they are to be used with an equation involving US units for surface area, thus producing results identical to those of reference [5].

It is also interesting to note that the correction factors in reference [13] are identical to those presented in reference [8]. However, reference [8] instructs that those factors be used with an equation involving SI units for surface area, which is incorrect.

Thus, with the aid of reference [13], it is apparent that both [7] and [8] make unit conversion errors, but in opposite directions. The scheme in reference [7] results in octave band levels that are overstated by 10 dB and the scheme in reference [8] results in octave band levels that are understated by 10 dB. With the correction of these errors, the factors presented in references [5], [7], [8] and [13] are all identical, and the basic correction factors of these references are all within just 2 dB of the preferred factors in references [7] and [11].