Improved CPX Enclosure Correction Measurements using a Maximum Length Sequence Impulse Response

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ABSTRACT

Waka Kotahi NZ Transport Agency utilises a Close Proximity (CPX) trailer-based system to measure tyre/road noise in general accordance with ISO 11819-2. ISO 11819-2 calls for a frequency dependent device correction to be determined for the CPX trailer system and applied to the measured noise levels. This correction is intended to adjust the measured noise levels based on the acoustic behaviour of the enclosure (modes and absorption), making the measured CPX noise levels independent of the enclosure.

The specified test method using steady state sound level difference for determining the device corrections has been found to be sensitive to background noise. An improved test method has been developed that utilises a Maximum Length Sequence (MLS) to measure impulse responses that are then used to determine the device correction. The MLS test method allows high signal-to-noise ratios to be obtained, allowing measurements to be performed in environments with relatively high background noise levels.

Inadequacies in the specified test method for correcting the measured noise levels have been identified in the results of annual CPX surveys. The sensitivity of the device correction to source characteristics and the CPX wheel enclosure layout have been investigated. The range of changes to the enclosure that these corrections are suitable for and associated impacts on the measured CPX level ($L_{CPX:P1,80}$) are discussed.

Three other measurement systems that utilise the MLS impulse response method have also been implemented: noise barrier transmission loss, noise barrier surface reflections, and road surface absorption. Learnings from these systems were applied to the development of the improved CPX device corrections methodology.

INTRODUCTION

Waka Kotahi operates a CPX trailer system for routine surveys of road surface noise, and research into low noise road surfaces [1]. This trailer-based system is based on ISO 11819-2 [2] and is equipped with enclosures over the wheels (see Figure 1). These enclosures protect the measurement equipment and reduce noise from passing vehicles.

Figure 1. Waka Kotahi trailer based CPX system.

Since the initial development of the Waka Kotahi CPX trailer system in 2016 ongoing modifications have been made to the trailer and wheel enclosures. Whenever changes are made to the enclosures a set of enclosure specific device corrections[1] are measured. The method described in ISO 11819-2 has been observed to be sensitive to background noise, resulting in unreliable corrections. An alternative method for determining the device corrections using an MLS signal to measure the impulse response of the enclosure is described and has been evaluated. This alternative method is less sensitive to background noise (as described in ISO 18233 [3]).

Additionally, the sensitivity of the device corrections to changes in the enclosure and noise source has been measured using the MLS impulse response methodology. The aim of these investigations is to quantify how well the current measurement approach and associated corrections recreate the real-world noise environment within the enclosure. ISO 11819-2 specifies a limit of ±3 dB for the device correction and this has been compared with the measured device corrections with different enclosures.

[1] Referred to as "device corrections" throughout this paper

ENCLOSURE SPECIFIC DEVICE CORRECTIONS

The device corrections are intended to remove the effect of reflections from the wheel enclosure, axle, and frame from the measured tyre/road noise. This method is described in Appendix A.2 of ISO 11819-2 and involves measuring the sound pressure level produced by a driver excited by a pink noise signal mounted in a tyre shaped enclosure. The sound pressure level is measured in the following configurations:

- On a reflective plane (hemi-anechoic) with no other reflective objects (Figure 2).
- Mounted to the axle of the trailer in the same manner as the actual tyre (Figure 3).

The plywood sheet shown in Figure 2 and Figure 3 holds the microphones in the locations specified by ISO 11819-2, this minimises changes in the microphone positions relative to the sound sources. The microphones are aligned with the existing mounts within the CPX enclosure.

Figure 2. Tyre shaped sound source on reflective plane.

Figure 3. Tyre shaped sound source mounted to CPX trailer.

The current (2024) Waka Kotahi CPX trailer is equipped to measure road surface noise at four microphone positions within the left wheel path enclosure. These microphone positions are shown in Figure 4 below. Microphone positions 1 and 2 are mandatory for all CPX measurements, and positions 4 and 5 are used for additional research purposes [4].

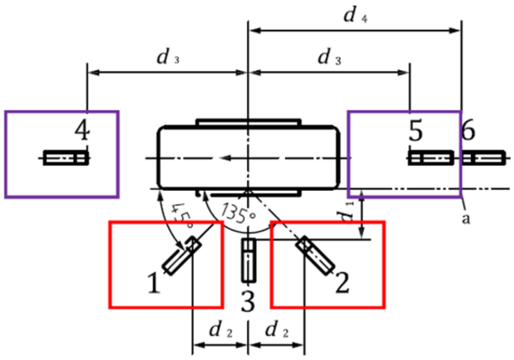

Figure 4. Microphone positions for CPX trailer (Reproduced from Figure 1 of ISO 11819-2)

The device corrections are calculated by subtracting the hemi-anechoic sound pressure level from the sound pressure level when mounted to the trailer, in one-third octave bands. ISO 11819-2 requires the calculated device corrections to be applied CPX noise level in one-third octave bands for each pair of microphones used during the measurements (microphones 1 and 2, and microphones 4 and 5).

ISO 11819-2 states that "*the effect of unwanted reflections shall not be more than 3 dB*". This has been interpreted to mean that the device corrections must be below 3 dB in all one-third octave bands. The modifications made to the enclosure are also intended to investigate if applying a threshold based on the measured device corrections is well suited to unwanted reflections.

The steady-state noise level method relies on a low and consistent background noise level. This is challenging to achieve in a suitably hemi-anechoic (i.e. open air) location that is convenient for testing and modifying the trailer. Variations in the background noise level between the hemi-anechoic and enclosure measurements can cause large variations in the measured device correction.

MAXIMUM LENGTH SEQUENCE SIGNAL AND IMPULSE RESPONSE METHOD

The use of an MLS-based impulse response is less sensitive to background noise, which allows for the measurement of the device corrections in a wider range of environments. The MLS impulse response allows the measurement to be repeated in a wider range of noise environments and increases the reliability of the corrections. This methodology has been developed from that described in ISO 18233, and implemented in ISO 13472-1 [5], EN 1793-5 [6] and EN 1793-6 [7]. The improved reliability and ease of measurement allowed for testing to be performed throughout the day when background noise levels are elevated. This facilitated the measurement of a range of enclosure and source arrangements as discussed in the following sections.

The MLS signal used in this methodology is a pseudorandom binary sequence that is deterministic in nature. This deterministic nature is used to recreate the input signal for the calculation of impulse responses.

The measurements are performed in the same manner as described in the previous section, with the pink noise replaced with the following MLS signal:

- An MLS cycle is generated with a specified sample rate and number of bits (nominally 51.2 kHz and 16 bits)

- This cycle is repeated several times with a specified (nominally 3) buffer cycles at the start and end which are not used in calculations. The number of times the cycle is repeated depends on the background noise, as a higher number of repetitions increases the signal to noise ratio.

The impulse response from the hemi-anechoic and enclosure measurements are calculated and aligned. The impulse response for the hemi-anechoic and enclosure measurements is calculated using the following steps:

- Generate the MLS cycle based on the sample rate and number of bits.
- Extract measured MLS cycles from the recorded signals and average these cycles.
- Calculate the ratio of input and output signals in the frequency-domain, then reconvert to the time-domain using an inverse FFT.
- Align the impulse responses by shifting the peak to a defined time.

An example of the measured impulse responses is presented in Figure 5.

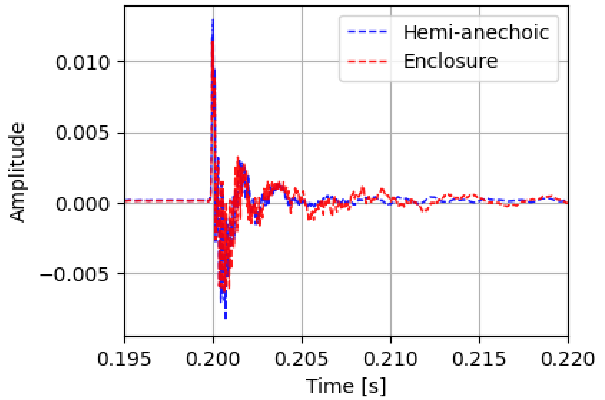

Figure 5. Example of measured impulse responses.

The one-third octave band impulse response of the enclosure measurement is subtracted from the hemi-anechoic measurement. This yields the device correction based on the impulse response method. Additionally, the signal to noise ratio (SNR) for both impulse responses is also calculated in each one-third octave band.

The SNR for the impulse responses presented in Figure 5 were 18 dB and 20 dB for the hemi-anechoic and enclosure measurements, respectively, which is typical of measurements using this method. These measurements were performed during the day with moderate background noise levels, which would have prevented measurements using the original methodology.

Enclosure and Source Tests

The measurements presented in this paper are intended to investigate two major factors:

1. To test if the device corrections could detect large changes in the enclosure, and if so to check if these applying the device corrections to measured CPX levels yielded consistent results.

2. To test if the device corrections were sensitive to large changes in the source design, and to evaluate if the associated device corrections impact the measured CPX levels.

Three enclosure variations were tested, these modifications were intended to cause large changes to the reflections within the enclosure. The variations were:

- Unmodified enclosure as used during routine CPX testing in 2023/2024. This variation forms a baseline to compare changes in the enclosure,

- Two reflective boxes installed within the enclosure. The boxes are intended to introduce a reflective surface in close proximity to each of the four microphones.

- Removal of the sound absorption from within the enclosure. This introduces reflective surfaces further from the microphones and in different orientations.

Two source arrangements were tested for each enclosure variation:

- The tyre shaped sound source as specified in ISO 11819-2 consisting of a 150 mm driver mounted in a wooden enclosure shaped like a tyre.

- A cuboid sound source consisting of a 200 mm speaker driver mounted in a 300 mm by 100 mm wooden box.

The three enclosure variations are shown in Figure 6, Figure 7 and Figure 8. The tyre shaped sound source is shown in Figure 6 and Figure 8, and the cuboid sound source is shown in Figure 7.

Figure 6. Unmodified enclosure (tyre shaped source).

Figure 7. Reflective boxes in enclosure (cuboid shaped source).

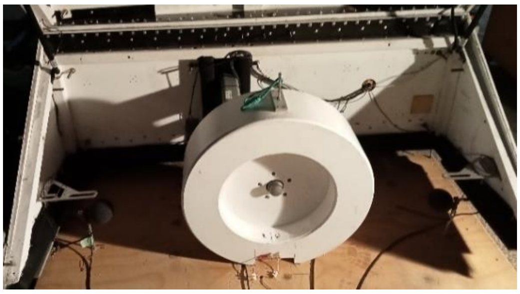

Figure 8. Absorption removed from enclosure (tyre shaped source).

For each variation the device correction was measured twice using the MLS impulse response method. The MLS measurement was repeated three times for each enclosure variation and sound source.

In order to test the effect of the enclosure modifications on the trailer during operation three CPX measurements were performed for each variation State Highway 1 between Sawyers Arms Road and The Groynes in Christchurch in the left lane.

No other changes were made to the CPX system throughout these measurements. Measurements were performed using the Standard Reference Test Tyre (P1) at 80 km/hr on both Porous Asphalt (PA) and Stone Mastic Asphalt (SMA). All CPX measurements were undertaken immediately after performing the device correction measurements.

RESULTS OF SOURCE TESTS

The effect of the changes to the sound source was evaluated by comparing the measured device corrections. The device corrections were found to be strongly influenced by the source type.

The change in device corrections for the two different source types when measuring the unmodified enclosure are shown in Figure 9. Microphones 1 and 2 had a maximum variation of 8.1 dB in the 2500 Hz band between the tyre shaped and cubic sources. Microphones 4 and 5 had a maximum variation of 12.8 dB in the 2500 Hz band between the tyre shaped and cubic sources.

RESULTS OF ENCLOSURE TESTS

Figure 10 presents the device corrections for each measured enclosure variation. The changes to the enclosure had a measurable effect on the device correction, with larger variations seen in microphone pair 4 and 5 when compared to microphone pair 1 and 2.

The changes made were intended to alter reflections within the enclosure, and it was expected that these reflections would cause the device corrections to exceed the ±3 dB limit specified in ISO 11819-2. Microphone positions 1 and 2 meet this limit in all one-third octave bands except 315 Hz for all the enclosure variations. As such, the measurement of the device correction and comparison with a threshold may not be the best tool for checking that the design of the enclosure sufficiently mitigates unwanted reflections.

The measured CPX one-third octave levels for the two enclosure variations were compared to the CPX level measured using the unmodified enclosure and standard device corrections. The difference between the standard CPX level, and both the uncorrected and corrected (using both the wheel shaped and cubic source) levels for both enclosure modifications were calculated for each measured 20 m road segment. These road segments are aligned using the trailer's onboard survey grade GPS and are expressed as road chainages.

Figure 11 Presents the mean differences in measured CPX level between the unmodified enclosure and the modified enclosure for each 20 m segment of PA10 (40 mm) measured. In this chart the unmodified enclosure results had the standard device corrections applied and represent the CPX level as measured during normal operation. The results seen in this chart are consistent with expectations, as the modified CPX levels deviate from the unmodified CPX levels.

Figure 12 presents the differences in CPX level after the device corrections (based on the tyre shaped sound source) have been applied to the modified enclosures. If the device corrections were to fully account for the changes to the enclosure the difference should be 0 dB in all one-third octave band, which is not the case. In some bands applying the relevant device corrections caused an increase in the difference between the CPX levels.

Figure 13 presents the same calculation as the second, but the device corrections used were derived using the cubic shaped sound source. Again, the expected result is a reduction in the difference to close to 0 dB, which is not seen. In many one-third octave bands the difference is increased by a large margin.

The analysis presented in the previous paragraphs was repeated for microphones 4 and 5, and for sections of SMA10 surface. In all cases the differences as a result of applying the corrections had similar trends. Larger differences were observed for microphones 4 and 5.

The difference in overall CPX levels in each 20 m segment measured for two selected surfaces (PA10 (40 mm) and SMA10) were compared in the same manner and are also presented in Figure 11, Figure 12 and Figure 13. For both surfaces the average difference in measured CPX levels varied by 1-4 dB between the standard CPX and the modified enclosures.

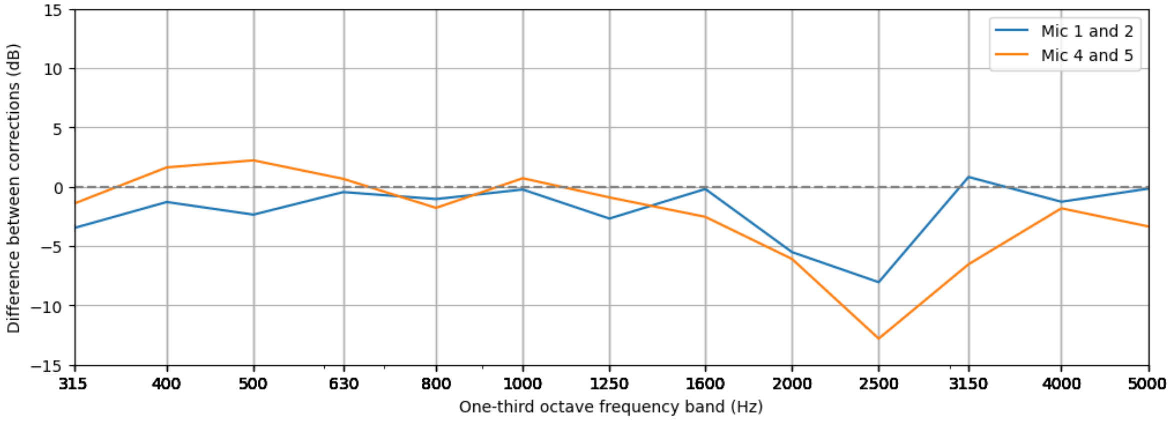

Figure 9. Difference between device corrections measured using cubic shaped source and tyre shaped source.

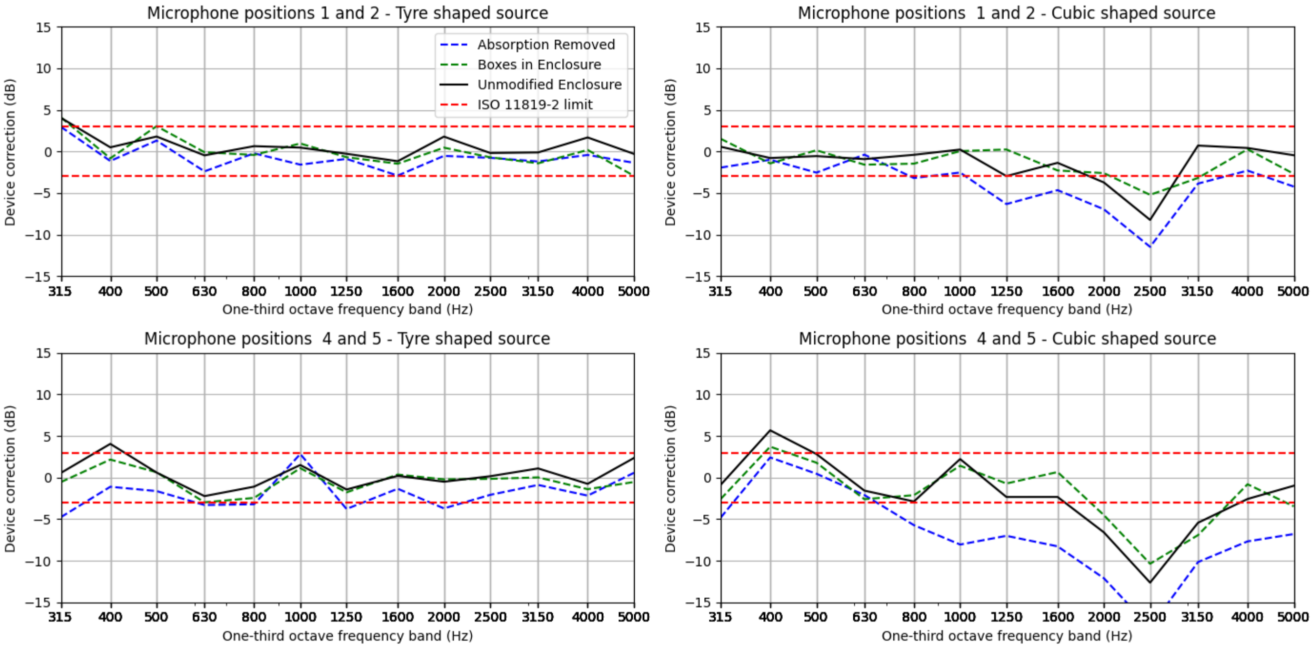

Figure 10. Measured device corrections for different source types, microphone positions and enclosure modifications.

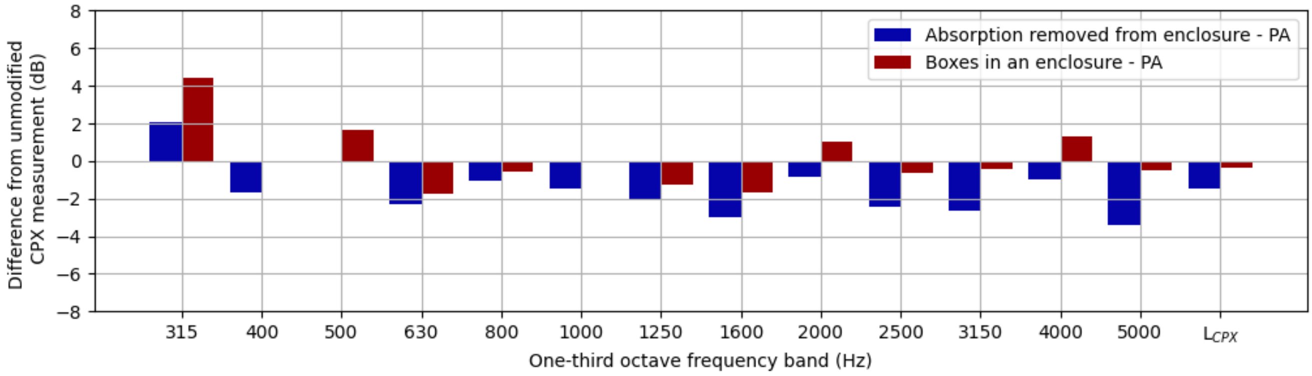

Figure 11. Difference between routine CPX results (unmodified enclosure, standard device corrections) and the two modified enclosure arrangements at microphones 1 and 2. No device corrections have been applied to the results of the modified enclosures.

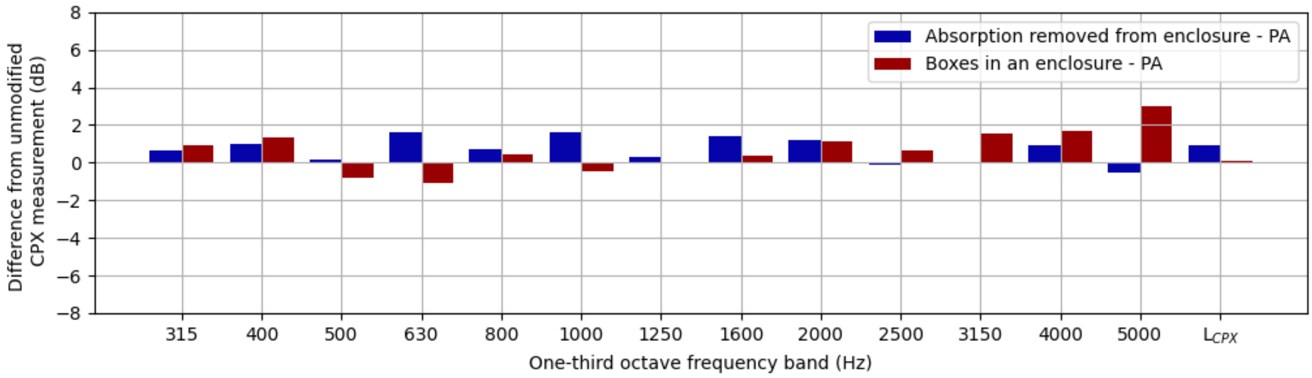

Figure 12. Difference between routine CPX results (unmodified enclosure, standard device corrections) and the two modified enclosure arrangements at microphones 1 and 2. The CPX levels from the modified enclosures have had device corrections applied based on measurements using the tyre shaped sound source.

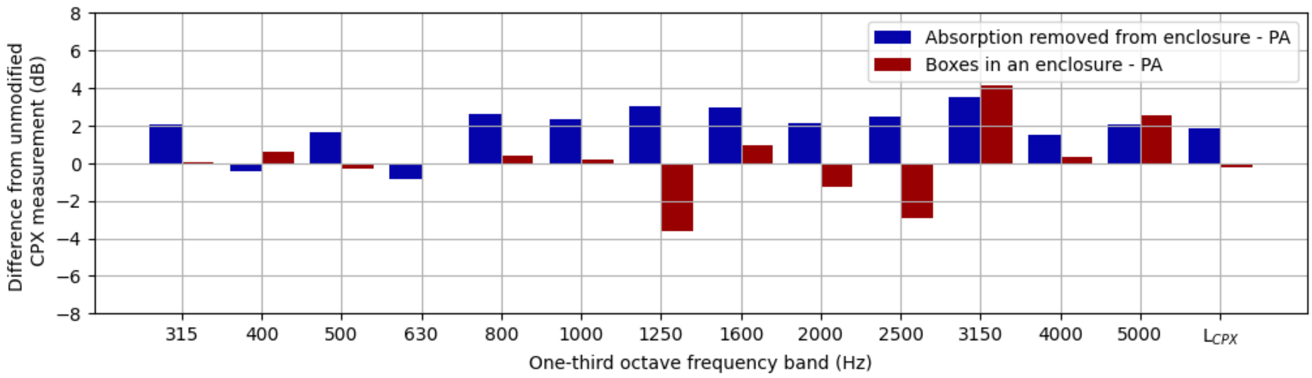

Figure 13. Difference between routine CPX results (unmodified enclosure, standard device corrections) and the two modified enclosure arrangements at microphones 1 and 2. The CPX levels from the modified enclosures have had device corrections applied based on measurements using the cuboid shaped sound source.

CONCLUSIONS

The use of an MLS impulse response for measuring the CPX device corrections has allowed for measurements to be performed in environments with higher background noise levels. This has enabled a wider investigation of the sensitivity of these device corrections to the sound source and enclosure layout.

The device correction was seen to be influenced by the sound source used. Further research will investigate the sensitivity of the device corrections to smaller changes to the sound source.

Applying the device corrections (using an tyre shaped source) were seen to reduce the variation between standard and modified enclosure CPX levels in most one-third octave bands. When the overall CPX levels for specific surfaces were compared the different enclosures yielded statistically different average levels. This indicates that the device correction does not fully capture the behaviour of the enclosure during CPX measurements. Further research will investigate the sensitivity of these device corrections to smaller changes, with an aim to identify limiting bounds for the application of the corrections, and to establish the contribution of the enclosure and device correction make to the overall uncertainty of the CPX measurements.

The modified enclosures meet the ± 3 dB requirement specified in ISO 11819-2 in most one-third octave frequency bands with all the absorption removed. This was not anticipated and may indicate that measuring the device corrections to a threshold may not be the most ideal tool for checking the effect of unwanted reflections within the enclosures.

ACKNOWLEDGMENTS

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