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INCREMENTAL USE OF FFT AS A SOLUTION TO MEASURE SHORT REVERBERATION TIMES IN LOW ONE-THIRD OCTAVE BANDS

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ABSTRACT

Measurements of reverberation time is often used to obtain information about sound absorption of rooms within building acoustics. A limitation of the common method used today is the performance of band-pass filters to process rapidly decaying signals in the low frequency range. This occurs when the reverberation time (T) and bandwidth (B) product is less than 16. This is a limitation in for instance multi-story timber buildings where low frequency range, below 50 Hz is of interest for impact sound performance. Here, an alternative method is tested. Using incremental short time steps between each FFT-calculation creates "moving average" signals, one for each frequency spectral line. A disadvantage is that the method requires a high dynamic range of the interrupted noise signals, which increases with frequency resolution. Here it is tested to fit in the frequency resolution to the one-third octave band frequency limits with as small errors as possible. It is shown that the dynamic range can be decreased a bit compared to a previously presented version. Two disadvantages with just one spectral line for each third octave band is that the signals are less stable and to produce the different frequency resolutions for each one-third octave requires more calculations.

Keywords: *Reverberation-time, Low-frequency, Impact-sound, Timber-building.*

1. INTRODUCTION

To achieve accurate data of sound absorption in rooms is an important part of sound insulation measurements within building acoustics. For multi-story timber buildings there may be a need to obtain information on sound absorption in low frequencies which is not typical for impact sound insulation measurements. Studies have shown that being able to measure down to 20 – 25 Hz [1, 2] is of interest in timber buildings since they tend to have their highest impact sound pressure levels in lower frequencies compared to, for instance, concrete floors. Standard impact sound insulation ratings (like $L'_{nT,w}$ or $L'_{n,w}$) are commonly made between 100 Hz to 3150 Hz and in some countries lower frequencies (in Finland and Sweden in the range from 50 to 3150 Hz). Two methods are generally used and established in field measurements of sound insulation (field measurements according to ISO 16283 which refers to ISO 3382-2 and ISO 18233 regarding reverberation time measurements). For the first method, reverberation time measurements are made with interrupted noise from a speaker (generating a broadband random noise), where the sound decay is measured, and band-bass filtered. These curves are then used for estimating the time of the sound to fall 60 decibels, commonly for one-third octave bands. The second method is the Integrated impulse response method, which uses the measured sound impulse. Impulse response used to be measured with excitation with for instance start pistol shots, balloon bursts etc. However, sine sweeps or maximum-length sequency (MLS) is more modern methods to measure the impulse responses in rooms (ISO 3382-1, De Cesaris et al. [3] is also a starting point for modern, alternative reverberation time estimation techniques). The decay curve for each octave band or one-third octave band is generated by a backward integration of the squared,

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filtered impulse responses, to estimate the same reverberation times. In most buildings and measurement situations, the standard methods are used with satisfying results. However, the two different methods have certain limitations in the lower frequencies. Band-pass filters (both digital and analog) have a maximum performance of how fast they can filter and follow a decaying signal accurately. If the signal drops faster than the performance of the band-pass filter manage, then one is measuring the performance of the filter instead of the sound signal. In ISO 3382-2 it is stated that the lower limit for reliable results caused by a filter, and a detector is:

$$BT > 16$$

where B is the filter bandwidth in Hertz, and T is the measured reverberation time in seconds. The same principle applies for rising signals. However, it has been shown that band-pass filters are commonly able to follow rising signals faster than decaying signals [4]. The integrated impulse response method allows a BT factor down to four (ISO 3382-1 and ISO 3382-2). For timber buildings where it is desired to be able to measure down to 20 Hz, it is seen that a BT-factor of four may still not be sufficient. In a previous published article in this project, Ref. [5], it was investigated whether using incremental time steps of interrupted noise signals with the Fast Fourier Transform (FFT) is a feasible way to measure and estimate shorter reverberation times (down to 0.1 s) in lower frequencies (down to 20 Hz). The results showed that it is possible. However, there are some weak parts. It was seen that there is a need for higher dynamic ranges in the interrupted noise signals. This is undesirable since it may require large equipment (loudspeaker and amplifier) to generate loud low frequency noise. It is also desired to have one-third octave results. A frequency resolution of 2 Hz was used, which gives a somewhat coarse agreement with the one-third octave band limits. In this study, it is investigated if optimization of the frequency resolution towards the one-third octave bands would be a way to improve the agreement in frequency band limits and to decrease the need of dynamic range in the interrupted noise signals.

2. METHOD

The incremental FFT-method is in principle the same as waterfall diagrams, with the difference that the decaying time signals are studied with high resolution (instead of the patterns of amplitudes in vibration analysis of machineries for example). Simplified, the FFT algorithm calculates the

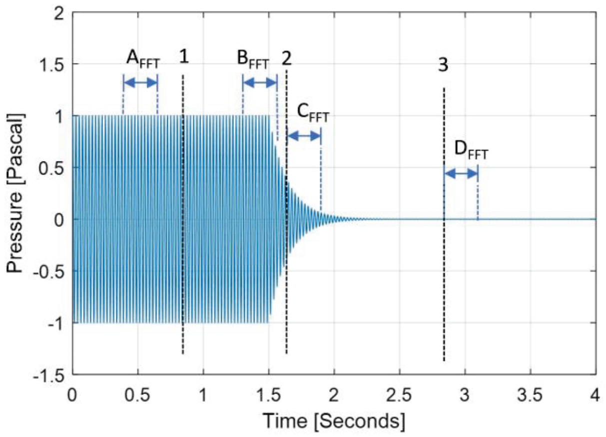

Figure 1. An artificial ideal interrupted ‘‘noise” signal. The signal is a 40 hertz sine with 60 dB decay in one second. The decay starts at 1.5 s and it decays until the 2.5 s mark. The number and letter designations in the diagram indicate points and intervals are also used in Fig. 2.

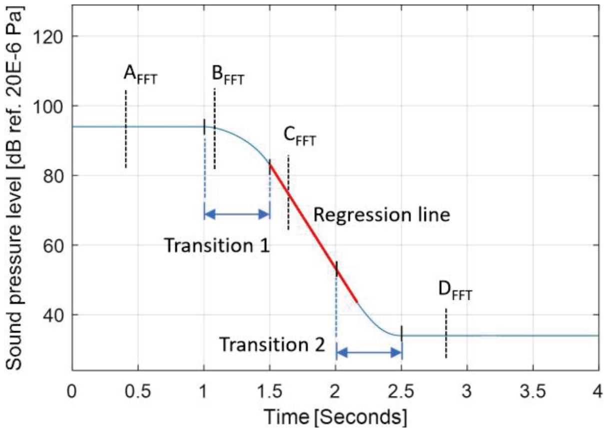

Figure 2. The incremental FFT calculation for the signal presented in Fig. 1. The notations in the figure are taken from Fig. 1. The B_{FFT} point indicates a point where the time signal has samples from both the steady state excitation part (here a sine signal but commonly noise in interrupted noise measurements) and the decaying part. The straight part (after transition 1 ended, until 10 dB above noise floor) exemplified by the C_{FFT} point and red line, is used to estimate the reverberation time by regression calculation.

Table 1. The one-third octave band limits aimed at when optimizing the frequency resolution.

Center frequency	Lower band limit	Upper band limit
(Hz)	(Hz)	(Hz)
16	14.1	17.8
20	17.8	22.4
25	22.4	28.2
31.5	28.2	35.5
40	35.5	44.7
50	44.7	56.2
63	56.2	70.8

frequency content in a discrete time series (in this case a measured signal with a decay). The frequency resolution (df) is the inverse of the calculation time of the FFT. For instance, a half second time (D) sequence for the FFT calculation will give a frequency resolution of 2 Hz (df= 1/D).

One clear advantage with this method is that the time signals in principle becomes moving averages for each frequency that the FFT is set to calculate. This makes decaying signal more stable compared to band-pass filtered signals. The disadvantage is that there will be two transition periods in the interrupted noise signal measurement. The transition periods occurs when the time signal that is calculated in the FFT covers both the steady state noise and the decaying signals. During this transition period the incremental FFT signal will not describe neither the steady state level nor the decay pace correctly. The second transition period occurs when the decaying signal reaches the noise floor. The principle is shown in Fig. 1 and Fig. 2. The calculation of reverberation time is done with regression analysis of the signal from when the first transition period ends, to when the decaying signal is at least 10 decibels above the steady state noise floor. In this work the frequency spectra of the FFT calculations are optimized to fit the lowest one-third octave bands. To have lowest possible transition time, one spectral curve covers a one-third octave band. This implies that the middle frequency between the FFT spectral results is here defined as the limits for the frequency bands calculated. It was seen that to have the smallest errors, the fourth spectral line could come close both in location of the frequencies and the frequency bandwidth, in relation to the one-third octave bands that was aimed. In Table 1, the correct one-third octave bands are presented. In Table 2, the optimized fourth spectral line in the FFT calculations, to fit the lowest one-third octave bands and its errors, are shown. In Table 3 the results and errors of Ref. [5] is presented, with 2 Hz resolution and the corresponding calculation of frequency deviation in relation the one-third octave bands. With the new one-third octave optimized settings the calculations are made in the same way as Ref. [5]. This means 100 different random noise signals were each sample is multiplied with a decaying curve corresponding to a perfect decay of 0.1 s, 0.5 s and 1.0 s. Each FTT calculation is made with 0.001 second increments (1000 Hz). These signals are then regression analyzed to extract reverberation times (after the first transition period ends and stops when the signal is 10 dB above the noise floor).

Table 2. The one-third octave limits and errors, here optimized for each one-third octave band. The band limits are here defined as the middle frequency to the adjacent spectral results.

Freq. res.	Center freq.	Lower band limit	Upper band Limit	Fq. limits error
(Hz)	(Hz)	(Hz)	(Hz)	(Hz)
3.97	15.9	13.9	17.9	0.3
5.00	20.0	17.5	22.5	0.4
6.25	25.0	21.9	28.1	0.6
7.89	31.6	27.6	35.5	0.6
10.00	40.0	35.0	45.0	0.8
12.50	50.0	43.8	56.3	1.0
15.75	63.0	55.1	70.9	1.1

Table 3. The one-third octave limits and errors of Ref. [5] with 2 Hz resolution (0.5 s transition time).

Freq. res.	Center freq.	Lower band limit	Upper band limit	Fq. limits error
(Hz)	(Hz)	(Hz)	(Hz)	(Hz)
2.0	16.0	15.0	17.0	1.7
2.0	20.0	17.0	23.0	1.4
2.0	26.0	23.0	29.0	1.4
2.0	32.0	29.0	35.0	1.3
2.0	40.0	35.0	45.0	0.8
2.0	50.0	45.0	57.0	1.1
2.0	62.0	57.0	71.0	1.0

3. RESULTS

In Fig. 3, a band-pass filtered interrupted noise curve of 50 dB and T = 0.1 s is plotted for comparison with the incremental FFT. In Fig. 4, a corresponding incremental FFT one-third octave band curve, from Ref. [5] with 2 Hz resolution is plotted. In Fig. 5, a corresponding example curve is plotted with the optimization made here, of the incremental FFT-bands. It is seen that the band-pass curve does not fulfill the BT-factor and is thus not correct. From Ref. [5], the curve is less shaky / more stable since it is an energy average of three FFT frequencies (2 Hz resolution). For the optimized Incremental FFT with just one frequency, the curve is less stable compared to Ref. [5].

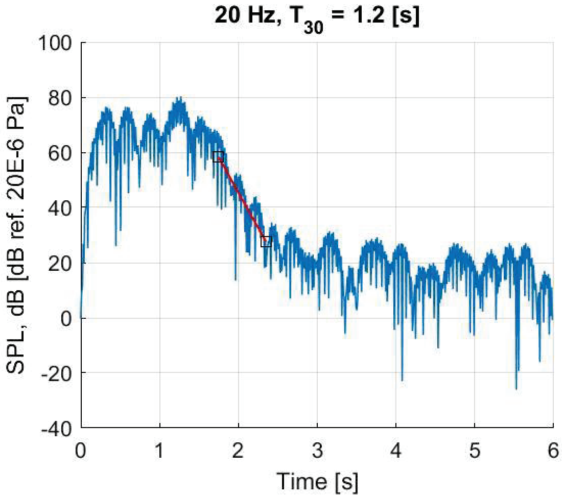

Figure 3. Example of an interrupted noise signal with a 50 dB drop. (a) A 20 Hz one-third bandpass filter (Butterworth order 5) is used in the regression analysis of the reverberation time. The signal is random with T = 0.1 s with the time for interruption of the noise at 1.5 s. The index at T in the header denotes the dynamic range in dB, used in the regression calculation of the reverberation time. The start and end of the regression calculation is marked with squares in the diagrams.

In Fig. 7 the reverberation time estimates from Ref. [5] are presented for comparison and in Fig. 8 the corresponding standard deviations are shown. The reverberation time results for all the optimized incremental FFT calculations are presented in Fig. 9 and in Fig. 10 their corresponding standard deviations. The optimized incremental FFT calculations are less stable compared to the Ref. [5] article incremental FFT calculation settings. In Fig. 6 the estimations are plotted for all hundred signals for T = 0.1 s, 25 Hz one-third octave band and 40 dB noise drop. It is seen that the instability in the noise signals, sometimes causes significant errors in the predictions. These extremes affect the average reverberation time value. Therefore, another set of results is presented where the five highest and five lowest outliers are removed from the results. These results are plotted in Fig. 11 and Fig 12. It is seen that regarding reverberation time accuracy, Ref. [5] have more even quality regardless of reverberation time, i.e., short, or long. For the optimized one-third octave, single frequency incremental FFT curves the most interesting results is the short reverberation time of 0.1 s. In this range the accuracy is competitive with the Ref. [5] calculation settings and results.

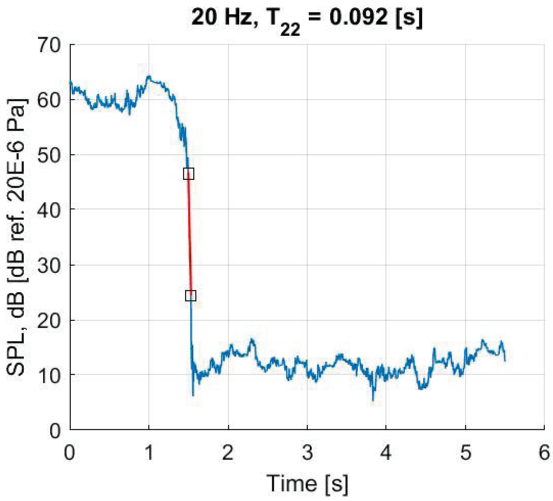

Figure 4. Example of an interrupted noise signal with a 50 dB drop (same as in Fig. 3) incremental FFT is used 2 Hz resolution i.e., from the Ref. [5]. The signal is random with T = 0.1 s. The start and end of the regression calculation is marked with squares in the diagram.

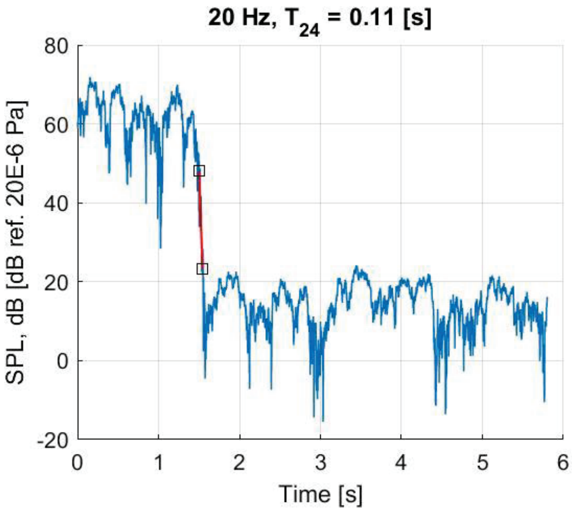

Figure 5. Example of an interrupted noise signal with a 50 dB drop (similar as in Fig. 3 and Fig. 4) incremental FFT with the optimized frequency resolution. The signal is random with T = 0.1 s. The start and end of the regression calculation is marked with squares in the diagram.

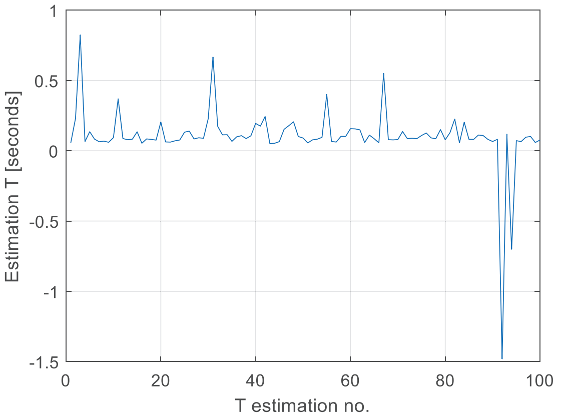

Figure 6. Estimations of the 0.1 second reverberation time signals (100 signals) from the regression analysis of the 25 Hz one-third octave band, with 40 dB drop.

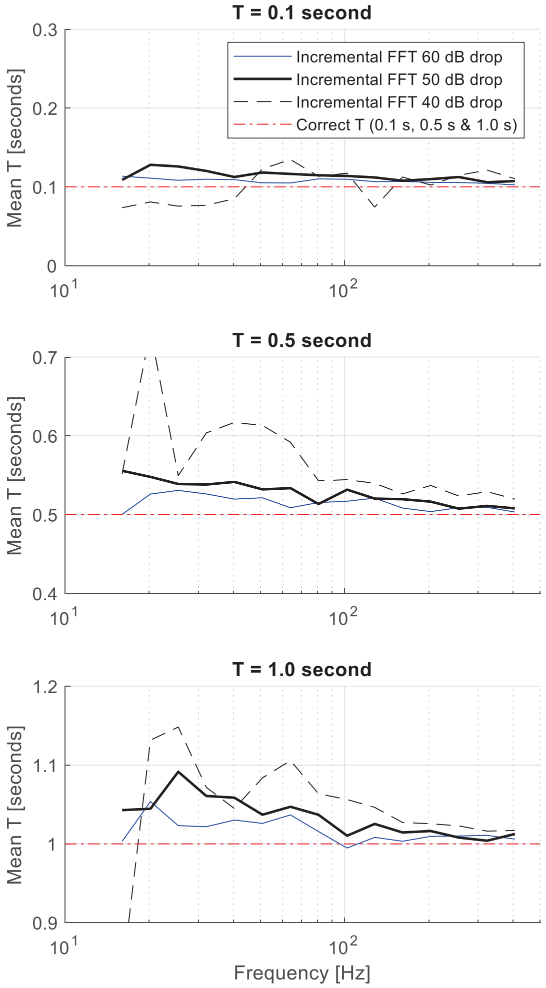

Figure 7. Mean reverberation time estimates compared to the true values, for regression analysis of the reverberation time for incremental FFT calculations in one-third octaves, with 2 Hz resolution. One hundred noise signals, with the same decay rate, have been used for each diagram.

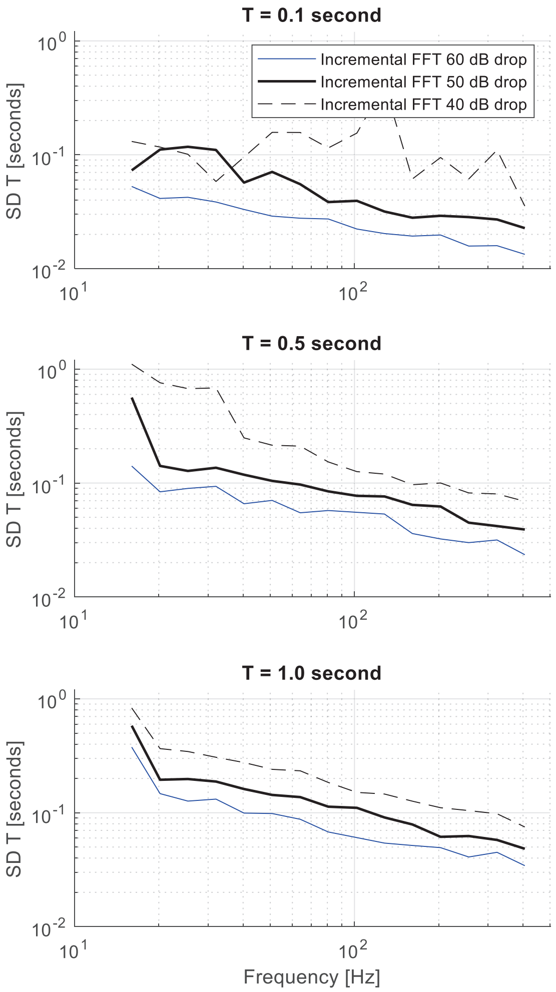

Figure 8. Standard deviations for regression analysis of the reverberation time for incremental FFT calculations in one-third octaves with 2 Hz resolution. One hundred noise signals, with the same decay rate, have been used for each diagram.

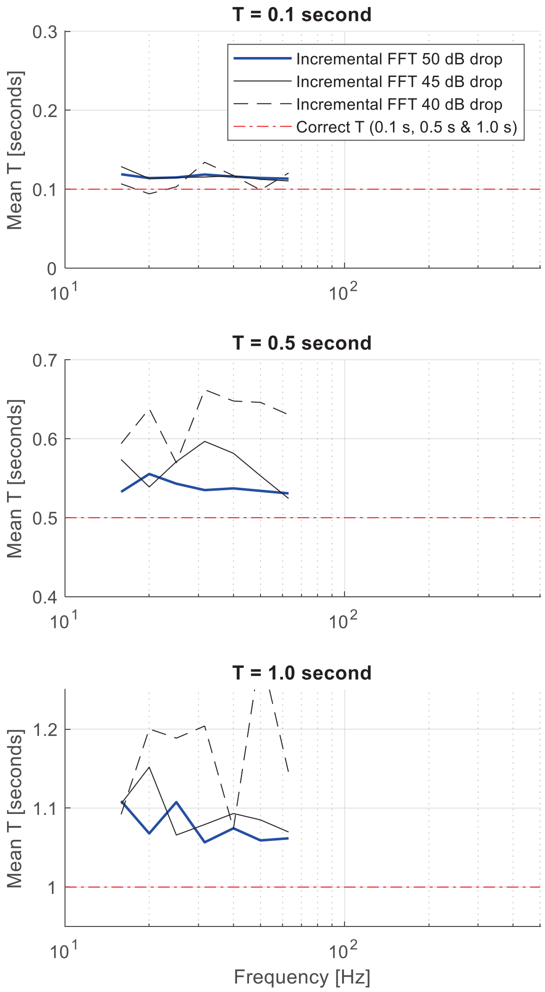

Figure 9. Reverberation time estimates for incremental FFT calculations with the optimized frequency resolution (fourth calculated frequency curve) against each presented one-third octave, compared to the true reverberation times. One hundred noise signals, with the same decay rate, have been used for each diagram.

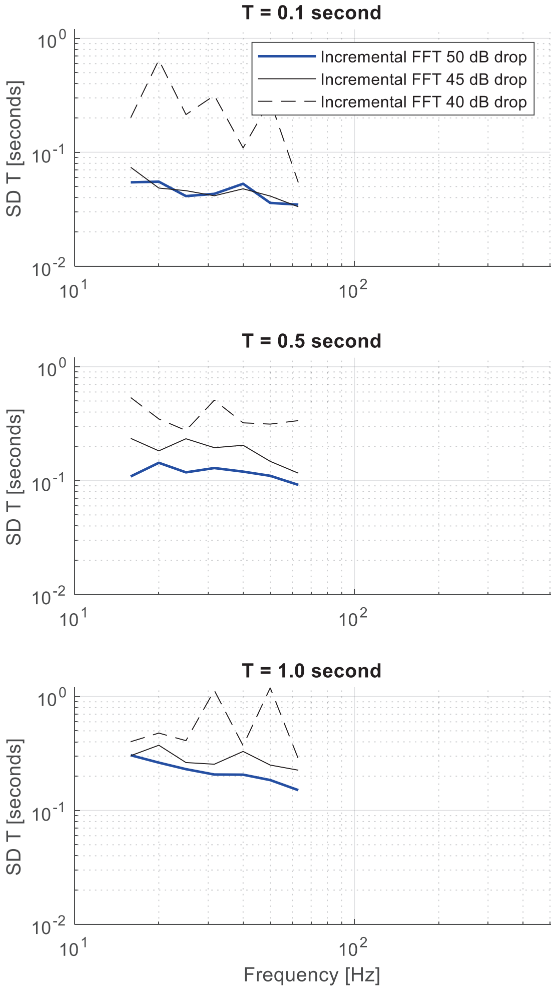

Figure 10. Standard deviations for regression of the reverberation time for incremental FFT calculations with the optimized frequency resolution (fourth calculated frequency curve) against each presented one-third octave, compared to the true reverberation times. One hundred noise signals, with the same decay rate, have been used for each diagram.

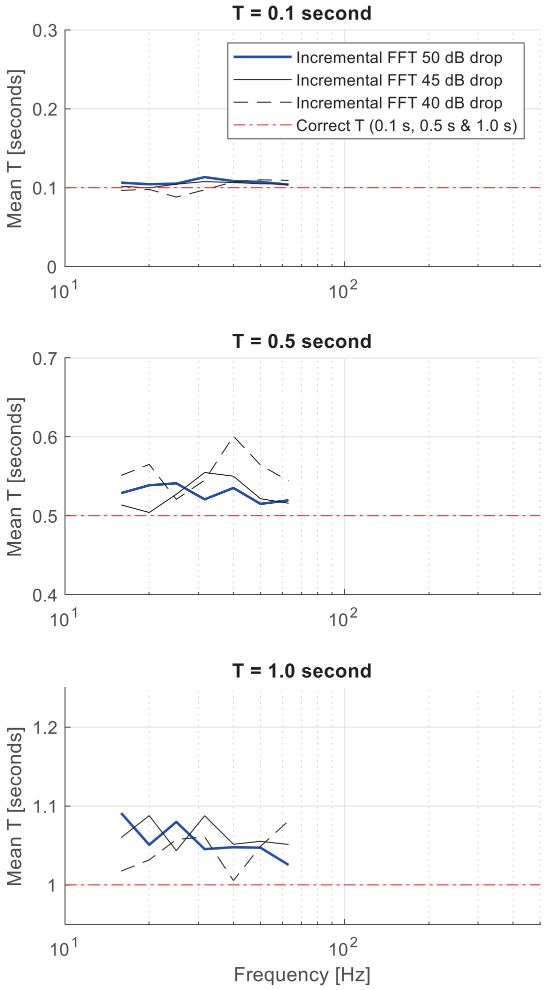

Figure 11. Reverberation time estimates for incremental FFT calculations with the optimized frequency resolution (fourth calculated frequency curve) against each presented one-third octave, compared to the true reverberation times. One hundred noise signals, with the same decay rate, have been used for each diagram. Here, the five highest and five lowest outliers removed.

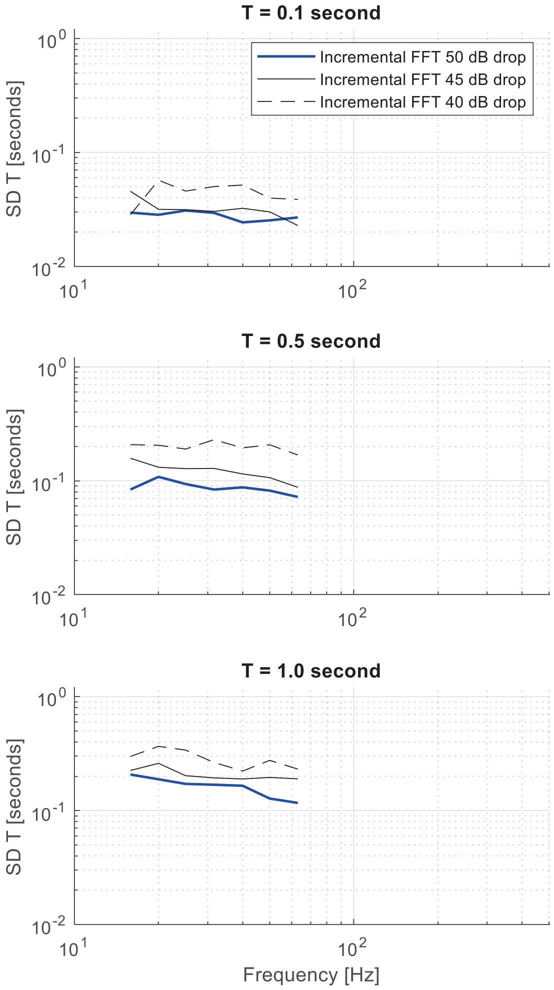

Figure 12. Standard deviations for regression of the reverberation time for incremental FFT calculations with the optimized frequency resolution (fourth calculated frequency curve) against each presented one-third octave, compared to the true reverberation times. One hundred noise signals, with the same decay rate, have been used for each diagram. Here, the five highest and five lowest outliers removed.

4. DISCUSSION AND CONCLUSIONS

For the shortest reverberation time (0.1 s), 40 dB drop seems sufficient with the one-third octave band optimized frequency resolution results, if the 5% of the highest outliers and 5% of the lowest outliers are removed. It is seen that at T = 0.5 s there is no improvement over Ref. [5].

The one-third octave band optimized results require more calculations compared to the settings of Ref. [5]. This since each third-octave band have its own frequency resolution, whereas results of Ref. [5] with 2 Hz resolution is used for all octave bands. The method with optimized bands and incremental FFTs is potentially useful, but just in the lowest frequencies and shortest reverberation times, and if one-third octave band information is needed. This since a 40 dB dynamic drop seems sufficient, if enough reverberation time values are collected, compared to 50 dB for the settings in the Ref. [5] results.

5. REFERENCES

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6. ACKNOWLEDGMENTS

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