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ASSESSING OUTDOOR SOUND ATTENUATION WITH SWEEPS IN A TIME-VARYING ATMOSPHERE

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ABSTRACT

Measuring outdoor sound attenuation is essential for various purposes, including studying outdoor sound propagation, evaluating noise prediction schemes, estimating attenuation when the simulation is not an option, or assessing the in-situ performance of noise abatement measures. A very successful technique that has superseded maximum length sequences (MLS) in room and building acoustics, sine sweeps have also been used outdoors. However, the outdoor environment is notoriously time-varying. There are claims that sine sweeps are less vulnerable to time variance, but no evidence for this. The purpose of this paper is to test these claims. The effect of time variance was investigated numerically in the theoretical case of a homogeneous flat ground and a time-varying non-homogeneous atmosphere. The impact of time variance on excess attenuation spectra is discussed in the corresponding time-invariant scenario. The results also indicate that sine sweeps perform better than MLS in the context of time variance.

Keywords: *sweeps, MLS-technique, outdoor sound attenuation, time-variance*

1. INTRODUCTION

The MLS-technique has been used for several decades to measure impulse responses and reverberation time in room and architectural acoustics [1–7]. The MLS-technique has also been used outdoors. [8–11]. It was, however, rapidly discovered that this method is sensitive to time variance in the system to be characterized [4].

Sine sweeps have become increasingly popular in recent years [12–14] and have superseded the MLS-technique in many cases due to their superior performance when it comes to sensitivity to noise [7, 14] and due to their ease of customizing to a specific range of frequencies. [13]. Moreover, it has been generally assumed that sweeps are more robust to time variance [13–15] than MLS.

For instance, although the ISO 18233 measurement standard allows for both the MLS-technique and sine sweeps, this document states that sine sweeps are less sensitive to time variance while emphasizing the importance of gaining a deeper understanding of the fundamental concepts that underlie the new measurement technique involving sweeps.

Despite the popularity of sine sweeps, their performance in linear time-varying outdoor channels has not been thoroughly studied, and no evidence has been provided to support the claim about their lower sensitivity to time variance. Outdoor sound propagation is notoriously time-varying, with changes in temperature, with wind and turbulence affecting sound propagation. It is therefore of the utmost importance to get better insight into the behaviour of sine sweeps in the presence of time variance before using this technique outdoors. This paper proposes a numerical investigation of the impact of time variance on outdoor sound attenuation, transfer function and impulse response measurements using both linear sweeps and MLS.

This paper is organized in the following manner. Section 2 introduces the theory of linear sweeps and MLS.

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Section 3 outlines the definition of a time-varying test case based on empirical data, and the signals considered in our numerical study. In section 4, results are presented and discussed.

2. BRIEF THEORY

2.1 MLS Technique

A maximum-length sequence (MLS) is a binary sequence that can be generated by properly tapped and initialized shift registers [16]. For use in acoustics, the $0s$ and $1s$ are converted into a bipolar signal with amplitude $\pm V_0$ [17]. One key characteristics of a maximum length sequence is that its circular auto-correlation function is a periodical series of Kronecker delta functions $\delta(n)$, which are shifted by a DC component as.

$$R^{\circ}_{xx}[n] = \sum_{m=-\infty}^{\infty} \delta[n + mL] - \frac{1}{L+1}, \quad (1)$$

the period $L = 2^N - 1$ given by the order N of the sequence [18]. Consequently, a circular cross-correlation between the original sequence $x[n]$ and the sequence $y[n]$ passed through the system under test results in the impulse response of the system,

$$R^{\circ}_{xy}[n] = \sum_{m=-\infty}^{\infty} h[n + mL] - \frac{1}{L+1} \sum_{i=0}^{L-1} h[i] \quad (2)$$

Nowadays, it is relatively easy to implement the circular correlation even for very long sequences by applying correlation directly in the frequency domain using the Discrete Fourier Transform (DFT) as

$$R^{\circ}_{x\tilde{y}}[n] = \frac{1}{L} \sum_{k=0}^{L-1} X[k]Y^{*}[k]e^{\jmath \frac{2\pi k n}{L}} \quad (3)$$

where $X[k]$ and $Y[k]$ are the DFTs of $x[n]$ and $y[n]$, and $*$ denotes the complex conjugate.

Further information on generating the MLS and the underlying theory can be found in [8, 17].

2.2 Linear Sweep

A sweep signal is a sinusoidal signal that exhibits a changing instantaneous frequency over time. A general mathematical definition of such a signal is

$$x_{sweep}(t) = A(t)sin[\varphi(t) + \varphi_0]. \quad (4)$$

where $A(t)$ with a constant amplitude envelope. The φ_0 and $\varphi(t)$ are the initial and instantaneous phases at a given time t, and usually, $\varphi_0 = 0$.

An important characteristics of sweep signals is the relation between frequency and time. The sweeps signals are so-called asymptotic signals, whose instantaneous frequency and group delay relation are approximately identical for the whole range of frequencies of interest [19]. That means we can calculate the instantaneous frequency from the instantaneous phase as [20].

The change in instantaneous frequency over time can be defined in various ways, with linear and exponential variations being the most common. While a linear sweep has a constant power spectrum density akin to white noise, the exponential sweep features a higher power spectrum density at lower frequencies, similar to pink noise [15]. This paper considers linear sweep signals for convenience. The distribution of power spectrum density does not matter here because background noise is not considered in our simulations. A convenient expression for a normalized linear sweep signal is given below:

$$x_{lin}(t) = sin\left[2\pi\left(f_1 t + \frac{f_2 - f_1}{2T}t^2\right)\right]. \quad (5)$$

Where f_1 is the start frequency at $t = 0$, and f_2 is the ending frequency at $t = T$. T is the duration of the linear sweep.

The Power Spectral Density (PSD) of the linear sweep is flat. The autocorrelation R_{xx} of a signal approximates a Dirac pulse.

3. MATERIALS AND METHODS

In order to test the claim that sweep signals feature a better immunity than the MLS-technique against time variance in the context of outdoor measurements, we first need to discuss linear time-varying systems. Second, we define an idealised outdoor test case featuring time variance. Third, we have to collect data about time variance. Fourth, we need to specify the parameters used to define the MLS and the sweep that were used in the comparison.

3.1 Linear time-varying systems

A linear system that exhibits variations over time and different characteristics at least at two distinct moments is generally called a "linear time-varying system" (LTV). If the LTV system changes due to some other factor without any direct connection between the system's input and output, it is considered to be linear "asynchronously" time-varying (LATV) [21]. Similarly, an outdoor acoustic channel varies with temperature and wind velocity changes, resulting in a linear time-varying acoustic channel characterized as LTVAC. Under the assumption of linearity, acoustic propagation through an outdoor environment, the general effects of propagation can be approximated as a convolution:

$$y(t) = x(t) * h(t, \tau) \tag{6}$$

where $x(t)$ is the transmitted signal, $y(t)$ is the received signal, and $h(t)$ is the impulse response of the acoustic channel. In the case of multipath acoustic propagation in a non-homogeneous environment, the time-varying channel impulse response can be written

$$h(t, \tau) = \sum A_i \delta\left(t - d_i / c_{\text{eff}}(z, t)\right) \tag{7}$$

where A_i represents the amplitude attenuation coefficient for each propagation path, d_i represents the propagation distance for each path, and $c_{eff}(z, t)$ represents the effective time-varying speed of sound, which is a function of height and time. We simplified the calculation by neglecting the changes in $c_{eff}(z, t)$ with respect to height and only considered changes with respect to time, denoted as $c_{eff}(t)$. This simplified calculation is used to determine the time-varying delay $\tau = t - d_i/c_{eff}(t)$.

In our scenario, time variance was limited to propagation delays. In practice, whatever the test signal used, a time-varying delay was implemented by computing the delay for each sample of the test signal. This resulted in an unevenly sampled signal that was interpolated using barycentric Lagrange interpolation [22] and re-sampled at the sampling frequency as the input signal. This was carried out independently for each channel before summing the re-sampled signals.

3.2 Test case

Our study considered a non-homogeneous atmosphere and a hard flat ground. The geometry of the test case is depicted in Figure 1 and modelled by Atmospheric-Bellhop [23]. The atmosphere is supposed to be subject to temperature changes, thereby causing the speed of sound to vary while the vertical sound speed gradient remains constant. Atmospheric attenuation is ignored. A source and a receiver are placed at a horizontal distance of 160 m from each other. The source and receiver are both at 4 m height above the ground. In that geometrical configuration, the path length difference between the direct and reflected path is 0.9198 m.

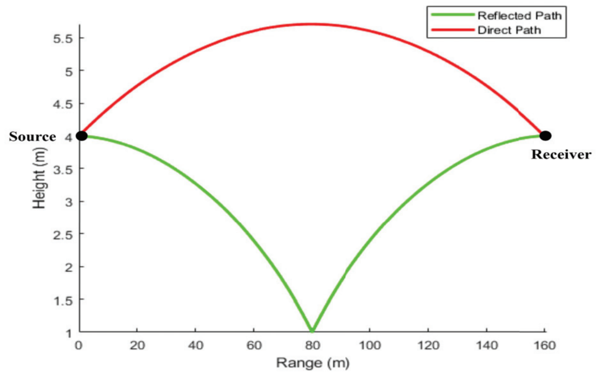

Figure 1. Geometry of the test case.

This test case can also be described as a time-varying comb filter.

3.3 Time-varying sound speed

In order to simulate time-variance in our test case, we used measurements carried out on October 17^{th}, 2019, in a crop field situated at Dragvoll (Figure 2), Trondheim, Norway. The speed of sound was collected with a 3D ultrasonic anemometer (Young type 81000) at 2 m height and 30 Hz sampling rate. The time series of c_{eff} that was recorded is presented in Figure 3.

Linear trends of the speed of sound over the duration of the test signal used in the simulations were extracted from this time series at different time intervals. This led to the *linearly increasing* sound speed and the *linearly decreasing* sound speed scenarios discussed in the results. A second group of scenarios considered added stochastic variations to the above-mentioned trends.

3.4 Signals and signal processing

The initial step involves generating two different input signals: 1) a linear sweep and 2) an MLS. The range of frequencies of interest goes from the lower transition frequency of the 63 Hz octave to the upper transition frequency of the 8 KHz octave band. The signals were sampled at $f_s = 44.1$ KHz. The duration T of both the sweep and the MLS was set to that of the shortest MLS that is longer than the expected impulse response of the system.

Figure 2. Aerial view of the location with the position of the ultrasonic anemometer on October 17th 2019.

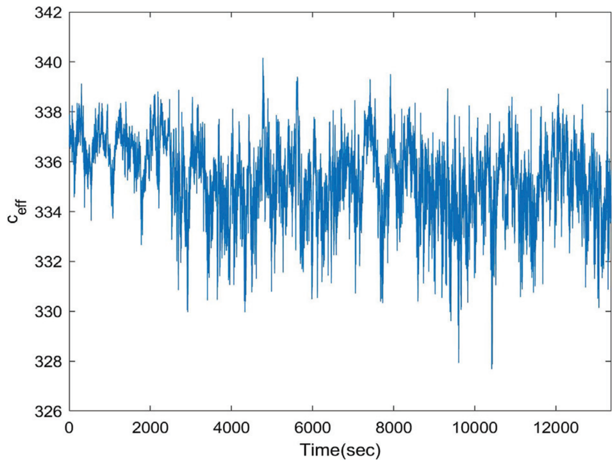

Figure 3. Time series of c_{eff} delivered by the ultrasonic anemometer at the selected location .

The aim was to ensure that the two signals would experience the same amount of time variance in the system.

From the simulated responses to the test signals, we then calculated the frequency response of the LTVAC. This was followed by using the inverse Fourier transform to obtain the corresponding impulse response. Literature suggests [13–15] two distinct deconvolution methods that leverage the fundamental properties of the corresponding excitation signals. The time-reversed filter technique is particularly effective for sweep signals, while the circular cross-correlation technique is more appropriate for MLS signals (see 2.1).

Most deconvolution techniques described in the relevant literature for sweep signals require using a version of the excitation signal that has been reversed in time. Following the recommendation given in Müller and Massarani [13], for linear sweeps, we used a time-reversed excitation signal for deconvolution of linear sweeps,

$$h(t) = y(t) * \underbrace{\mathrm{IFT}\left\{\frac{X(-f)}{|X(-f)|^2}\right\}}_{f_{tr}(t)} = y(t) * f_{tr}(t), \quad (8)$$

where $f_{tr}(t)$ is the time-reversed filter that can retrieve the impulse response of the system independently whether the excitation signal has a perfectly at spectrum or not.

4. RESULTS

The results of the study include the frequency responses (FRs), impulse responses (IRs), and the impact of time variance on excess attenuation (EA) spectra, which are presented in detail in this section.

Figure 4 illustrates the frequency responses (FRs) of both LTVAC and LTIC. Both exhibit the expected comb filter pattern that corresponds to interferences caused by the path length difference between the direct and the reflected component. When c_{eff} is a linear function of time, the FRs remain qualitatively identical to that of the LTIC for linear sweeps across the full range of frequencies of interest (see Fig. 4 (a) and (b)), although errors are observed in the frequencies of the dips. The effect of that kind of time variance is much more apparent with the MLS-technique (see Fig. 4 (c) and (d)), especially at higher frequencies where a large number of spurious peaks occur whose amplitude increases with frequency. These peaks blur the interference pattern. Furthermore, the linear sweep technique leads to much smoother curves than the MLS-technique when stochastic variations are added to the variation of sound speed (see Fig. 4 (e) - (h)).

Figure 5 allows us to compare the impulse responses (IRs) obtained using the linear sweep and MLS techniques for LTVAC. IRs are successfully retrieved when c_{eff} is a linear function of time in the cases where a linear sweep is used as the excitation signal. Two distinct arrivals are detected. They are separated by a delay that matches the path length difference (see Fig. 5 (a) and (b)). On the contrary,

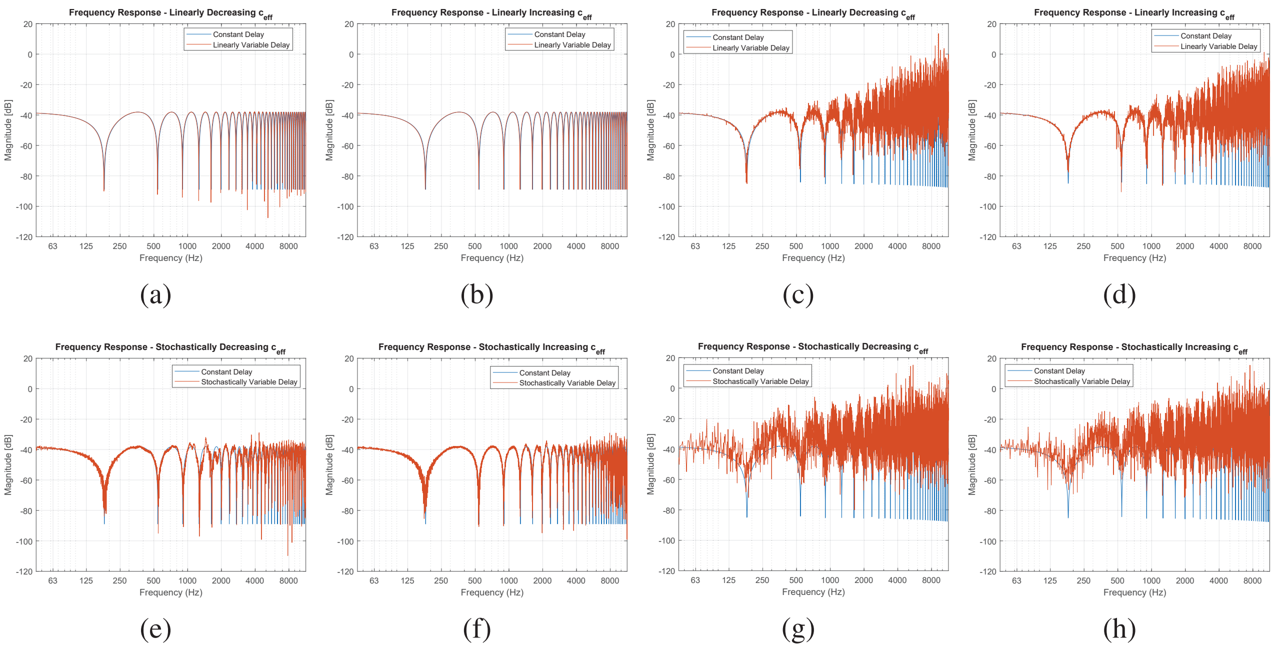

Figure 4. Frequency Response comparison between the linear time-varying acoustic channel (red) and the linear time-invariant acoustic channel (blue). The effect of linearly varying c_{eff} on FRs, (a)-(b) for linear sweep (c)-(d) for MLS. (a) and (c) correspond to decreasing, (b) and (d) to increasing c_{eff}. The effect of stochastically varying c_{eff} on FRs is presented in (e)-(f) for the linear sweep and (g)-(h) for MLS (e) and (g) correspond to decreasing, and (f) and (h) to increasing c_{eff}.

on the IRs obtained using the MLS-technique, no clear arrival can be distinguished. When a stochastic component is added, the linear sweeps still give distinct arrivals, although their interpretation is not straightforward (see Fig. 5 (e) and (f)). In the case of the MLS-technique, the dilution of the impulse response worsens compared to the purely deterministic case (see Fig. 5 (g) and (h)).

We also assessed the impact of time variance on excess attenuation by computing attenuation in $1/3$rd octave bands, and the results are depicted in Figure 6. When c_{eff} is a linear function of time, higher frequencies display less deviation from the LTIC (see Fig. 6 (a) and (b)). At lower frequencies, the number of interference dips within a one-third octave band is low so that a mispositioned dip leads to more visible effects on the $1/3$rd octave band level.

With the MLS-technique, the discrepancies with respect to the LTIC are larger than with the sweep. But like for the sweep, deviations from the LTIC a more visible for frequency bands where there are interference dips, but their density is low. When stochastic variations of c_{eff} are added, deviations from the LTIC are no longer limited to the lower frequencies.

5. CONCLUSION

This paper considered the claim that sine sweeps are less vulnerable to time variance than the MLS-technique. The effect of time variance was investigated numerically for one source-receiver configuration above a hard flat ground in the case of an idealized atmosphere subject to temperature variations.

The effect of time variance was illustrated on the frequency response, on the impulse response, and on the excess attenuation in $1/3$rd octave bands. First, the linear sweep performed much better than the MLS technique and exhibited stronger immunity against time variance in this simulated outdoor measurement test case. Second, the effect of time variance was most visible in the impulse response. With the linear sweep, the direct and the reflected pulses remained clearly visible, at least when the speed

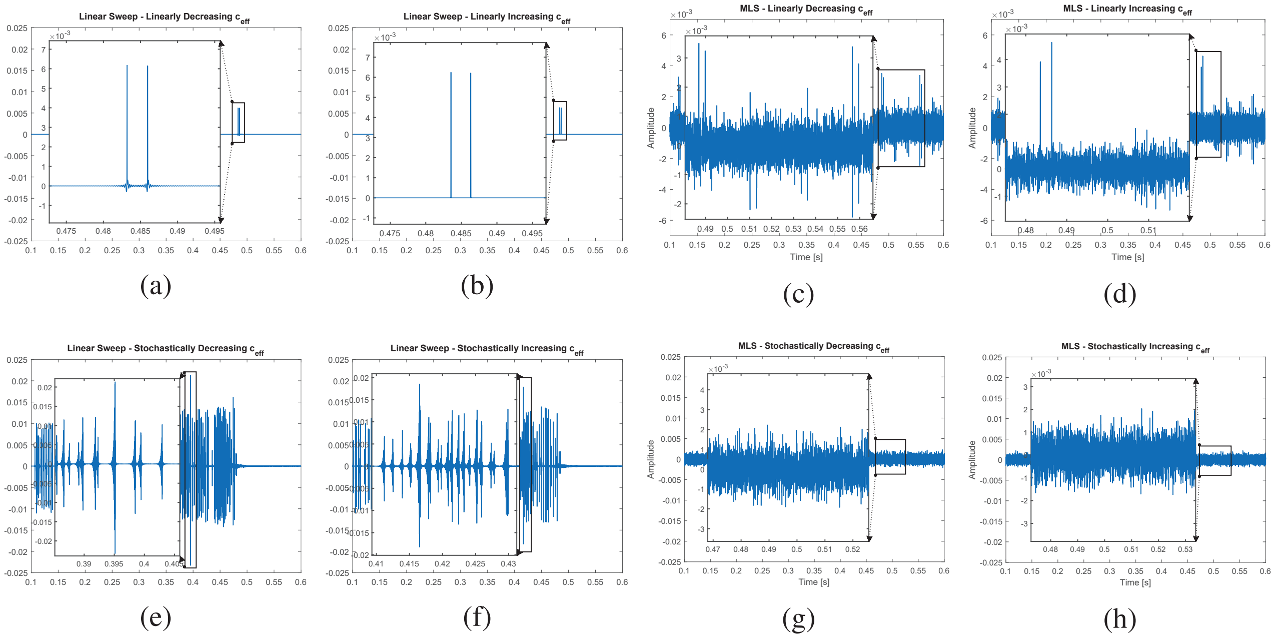

Figure 5. Impulse Response: The effect of linearly varying c_{eff} on IRs, (a)-(b) for linear sweep (c)-(d) for MLS, from decreasing to increasing c_{eff}. The effect stochastically varying c_{eff} on IRs, (e)-(f) for the linear sweep and (g)-(h) for MLS, from decreasing to increasing c_{eff}.

of sound was a linear function of time. This was not the case with the MLS-technique. The paper provides material supporting the claim that linear sweeps are a better option for characterizing linear systems that are subject to time variance. To the authors' knowledge, this is the first published investigation of the comparative robustness of linear sweeps and of the MLS technique against time variance in outdoor environments.

However, the test case considered in this numerical study includes a number of simplifications. Additional research is required to examine the impact of time-variance in more realistic situations.

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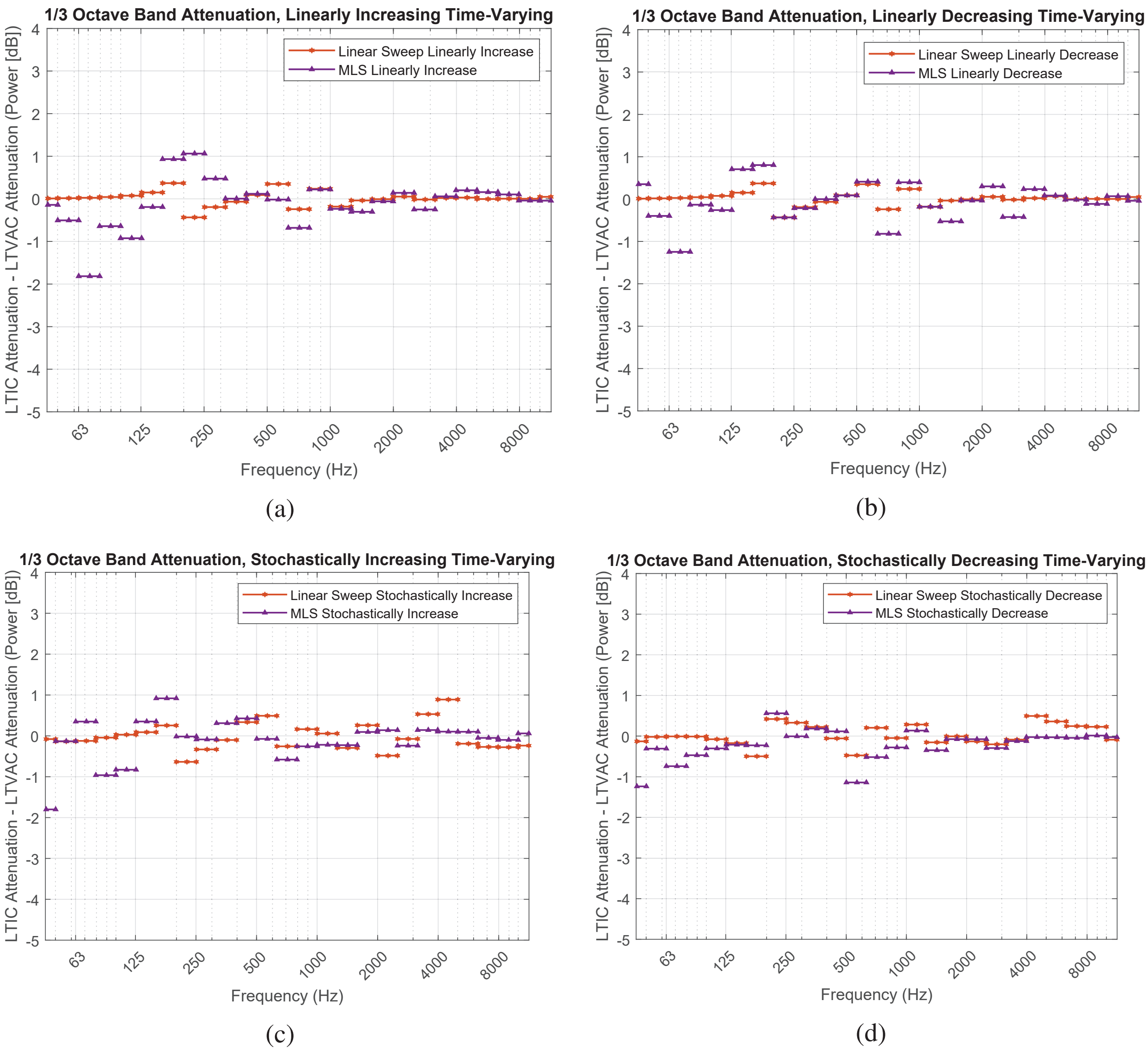

Figure 6. Attenuation: The x-axis represents The range of frequencies of interest from lower octave frequency $f_1 = 63$ Hz to upper octave frequency $f_2 = 8$ KHz. The y-axis represents the attenuation in terms of *LTIC - LTVAC* in dB.

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