IMPULSE RESPONSE MEASUREMENT WITH SINE SWEEPS AND AMPLITUDE MODULATION SCHEMES

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ABSTRACT

Sine sweeps used as excitation signals provide a way to measure linear impulse response and harmonic distortion simultaneously. This technique is applicable to measurements of room acoustics as well as audio equipment. In this paper, both linear sweep and exponential sweep measurement procedures and results are presented. A novel amplitude modulation scheme for exponential sweep measurement is also described.

Index Terms— Impulse response measurement, Amplitude modulation

1. INTRODUCTION

The characteristics of a linear, time-invariant component of any system are fully described by its impulse response $h\,(t)$. It is thus desirable to acquire the impulse response as accurately as possible. In traditional impulse response measurement, periodic pulse and Maximal-Length Sequence (MLS) are often used as excitation signals [1]. Periodic pulse testing is the simplest and most intuitive method but usually results in a poor SNR due to the requirement of low energy stimuli to prevent non-linear distortions in the output. MLS stimuli is typically employed to improve the SNR. However, in real-world systems there are always non-linearities (e.g. in any electro-mechanical transducer) [2]. Using traditional methods the non-linear response can not be separated from the linear response. The use of linear sine sweeps have been attempted but the separation of linear response and non-linear distortions remain elusive - especially in low frequency regions.

An alternative impulse response measurement method has been developed in [2]. In this technique, a log-swept sine stimulus was employed where the frequency varies exponentially as a function of time over the range of interest. The output of the system in response to this stimuli consist of both linear response to the excitation and harmonic distortion at various orders due to the inherent non-linearity in most systems. The deconvolved output presents a clean separation of linear response and harmonic distortion, which allows the linear response to be delineated. It is also possible to characterize the harmonic distortions if required. Further, the exponential sine sweep provides a considerable advantage with regards to SNR compared with linear sine sweep [3], periodic pulse or MLS[1] techniques.

Unlike linear-swept sine signal, the exponentially-based chirp signal sweeps much faster in higher frequency regions than lower frequency regions [4]. This introduces energy differences between low and high frequencies which makes the spectrum of signal non-flat. In this paper, a novel amplitude modulation scheme is introduced which allows modifying the frequency content of the log-swept signal rather than the inverse filter as proposed in[2]. This reduces the amount of post-processing , offering greater convenience and flexibility while maintaining accuracy.

2. IMPULSE RESPONSE MEASUREMENT

The impulse response measurements were carried out in a concrete and carpeted conference room of size 4.9m x 6.4m x 3.3m. Linear and exponential sine sweeps were played out through a loudspeaker (Genelec 8030A) and recorded using an omni-directional microphone (B&K Type 4189). The loudspeaker was connected to an RME multiface device which was interfaced to a computer. The microphone was interfaced to a computer via an appropriate preamplifier and another RME multiface device. Both playback and recording was carried out at 44.1kHz sampling rates and with 16bits/sample resolution. The time domain deconvolution operation was then applied . For linear sine sweep the inverse filter is simply the time reversed version of the stimuli itself, while for exponential sine sweep, an amplitude modulation is needed [2].

2.1. Linear sine sweep measurement

A linearly varying-frequency sine sweep can be described mathematically as [2]:

$$s(t) = \sin[\theta(t)] = \sin(\omega_1 t + \frac{\omega_2 - \omega_1}{T} \cdot \frac{t^2}{2}) \qquad (1)$$

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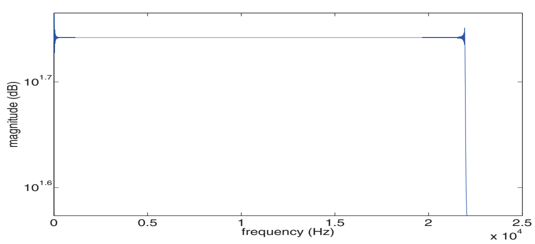
Where ω_1 and ω_2 are the start and end frequencies respectively, T is the time duration in seconds. The instantaneous frequency $\omega(t)$ is thus given by:

$$\omega(t) = \frac{d[\theta(t)]}{dt} = \omega_1 + \frac{\omega_2 - \omega_1}{T} \cdot t \quad (2)$$

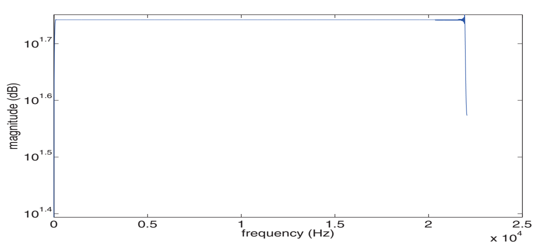
Since the energy in a varying-frequency signal at any frequency is proportional to the time spent at that particular frequency, where $\omega'(t)$ represents the time rate of change of the frequency. The energy of linear sine sweep as a function of time is given by:

$$E(t) \propto \frac{1}{\omega'(t)} = \frac{T}{\omega_2 - \omega_1} \quad (3)$$

It is obvious that the energy is constant for all frequencies. The spectrum of the linear sine sweep is shown in Figure 1 together with the spectrum of inverse filter which is the linear sine sweep signal reversed along the time axis. The starting frequency $\omega_1 = 22$ Hz and ending frequency $\omega_2 = 22,000$ Hz are chosen in order to cover the hearing range of human ear. The time duration T is set to 15 seconds.



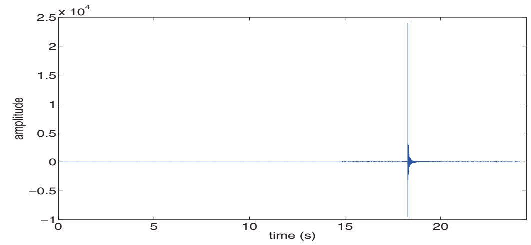
(a) linear sine sweep



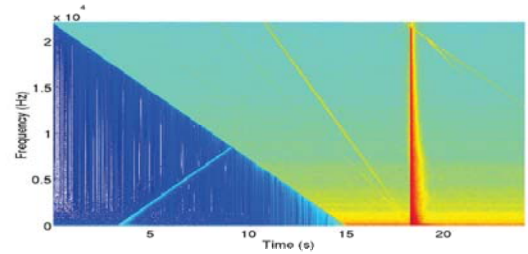
(b) inverse filter

Fig. 1. Magnitude response of linear sine sweep

As indicated in figure 1, both the linear sine sweep and the inverse filter have a flat spectrum, thus no amplitude modulation is required. The impulse response can be simply obtained by convolving the measured microphone signal with the inverse filter. The result is shown in Figure 2 together with its spectrogram. It can be observed that linear response appears as a straight vertical line followed by some kind of tail which represents the room reverberation. The non-linear distortions are a group of straight lines situated at left with increasing slopes.



(a) impulse response



(b) spectrogram

Fig. 2. Measured impulse response using linear sine sweep

2.2. Exponential sine sweep measurement

The general form of an exponentially swept sine signal is:

$$s(t) = \sin[\theta(t)] = \sin[K \cdot (e^{\frac{t}{L}} - 1)], \quad (4)$$

where

$$K = \frac{T \cdot \omega_1}{\ln(\frac{\omega_2}{\omega_1})}, L = \frac{T}{\ln(\frac{\omega_2}{\omega_1})} \quad (5)$$

and ω_1 and ω_2 are the lower and higher extremeties of the frequency range of the measurement, respectively. T is the time duration in seconds. The instantaneous frequency $\omega(t)$ now can be described as:

$$\omega(t) = \frac{d[\theta(t)]}{dt} = \frac{K}{L} \cdot e^{\frac{t}{L}} \quad (6)$$

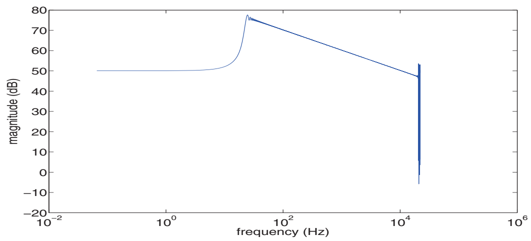
Look at the energy signal again, $E(t)$ is related to the frequency changing rate as:

$$E(t) \propto \frac{1}{\omega'(t)} = \frac{L^2}{K} \cdot e^{-\frac{t}{L}}, \quad (7)$$

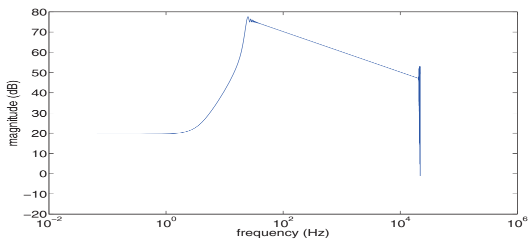
Thus, as a function of frequency, the energy $E(\omega)$, is given by:

$$E(j\omega) = \frac{kL^2}{K} \cdot \frac{1}{L + j\omega} \quad (8)$$

Where k is a constant of proportionality. Obviously,the energy drops while frequency increases. Further more, there is a factor $\frac{1}{\omega}$ in the equation. If the frequency doubles, this factor becomes $\frac{1}{2\omega}$, which will introduce approximately -3dB $(10log_{10}\frac{1}{2})$ energy drop. Things are the same for the time-reversed sine sweep signal, its energy spectrum falls by -3dB/octave as well. These are indicated in Figure 3.



(a) exponential sine sweep



(b) time reversed exponential sine sweep

Fig. 3. Magnitude response of exponential sine sweep

In order to compensate for the energy differences and get a flat spectrogram, an amplitude modulation is needed.The modulation method suggested by Farina [2] is applying an amplitude envelope of +6dB/octave to the time reversed signal's spectrum which makes it go up by +3dB/octave [3]. In this way both the sine sweep signal and the time reversed signal are compensated. Since the time reversed signal sweeps from high frequency to low frequency along time axis, the modulation envelop will be -6dB/octave and +6dB/octave when viewed in time domain and frequency domain respectively. This scheme can be termed post-modulation and its general form can be defined as:

$$m(t) = \frac{A}{\omega(t)} = A(\frac{K}{L} \cdot e^{\frac{t}{L}})^{-1} \quad (9)$$

Arbitrarily assigning the value of m(t) = 1 at t = 0, the scalar factor A can be solved as ω_1. Thus modulation function can be described as:

$$m(t) = \frac{\omega_1}{\omega(t)} = \frac{2\pi \cdot f_1}{\omega(t)} \quad (10)$$

The inverse filter of the exponential sine sweep is shown in Figure 4. It is clear that the magnitude of the modified inverse filter goes up while frequency increases. The impulse response measurement was taken under the same experimental conditions as the linear sine sweep measurement. The deconvolved impulse response and its spectrogram are shown in Figure 5. As the spectrogram reveals, the harmonic distortions are all straight vertical lines parallel and to the left (on the time axis) of the linear response. The harmonic distortions are located at precise anticipatory times on time axis [2]. This obviously offers a better separation between linear response and non-linear distortion.

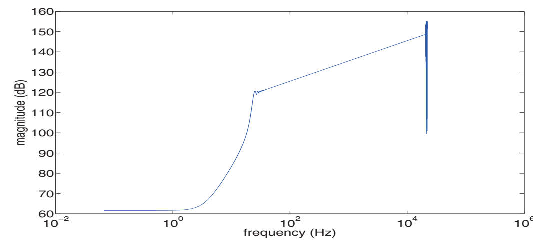
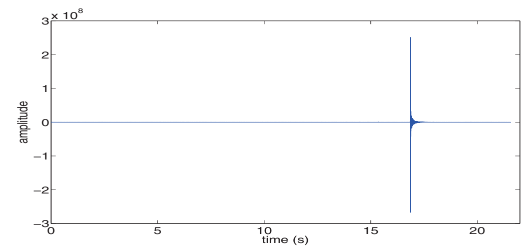
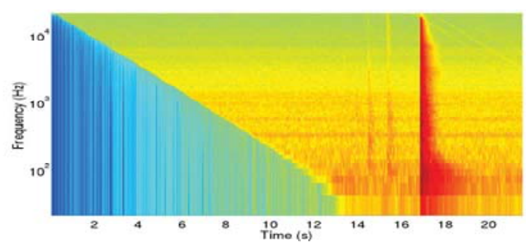


Fig. 4. Magnitude response of inverse filter using exponential sine sweep



(a) impulse response



(b) spectrogram of impulse response

Fig. 5. Measured impulse response and spectrogram using post-modulation method

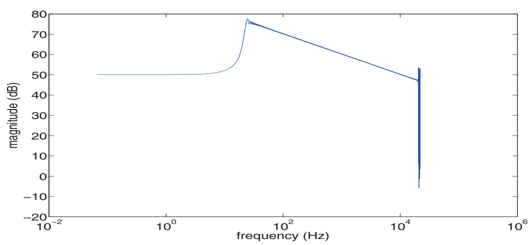
2.3. A new amplitude modulation scheme

Instead of modulating the time reversed signal, amplitude modulation can be implemented directly to the input sine sweep signal, this is called pre-modulation. Since the sine sweep signal's spectrum is falling by-3dB/octave, a modulation function with +3dB/octave can be employed to make its spectrum flat as shown in Figure 6. Obviously, the time reversed signal will have a flat spectrum as well which makes it the inverse filter of the measurement process, this is shown in Figure 7. In this modulation scheme, the sine sweep signal sweeps from low frequency to high frequency along time axis and the modulation envelop will be +3dB/octave viewed in both time and frequency domain. The general form of 3dB/octave is :

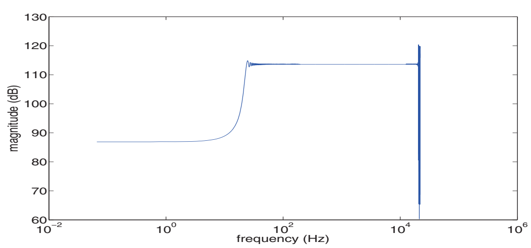
$$n(t) = B \cdot \sqrt{\omega(t)} \tag{11}$$

Arbitrarily setting the value n(t) = 1 at t = 0, the scale factor B can be solved as $\frac{1}{\sqrt{\omega_1}}$. Thus modulation function can be given as:

$$n(t) = \sqrt{\frac{\omega(t)}{\omega_1}} = \sqrt{\frac{\omega(t)}{2\pi \cdot f_1}} \tag{12}$$



(a) exponential sine sweep



(b) magnitude modulated exponential sine sweep

Fig. 6. magnitude response of modulated exponential sine sweep

The same measurement condition was used for the pre-modulated sine sweep again. From the graphs in Figure 8, it can be observed that the impulse response is as clean as the one we get using post-modulation and the harmonic distortions are also strictly parallel straight lines. However, it is noticeable that due to our arbitrary choice of n(t) = 1 at t = 0, the SNR at extremely low frequencies is not as high as the impulse response extracted by the post-modulation method. This can be improved by selecting a higher value of n(t) at t = 0.

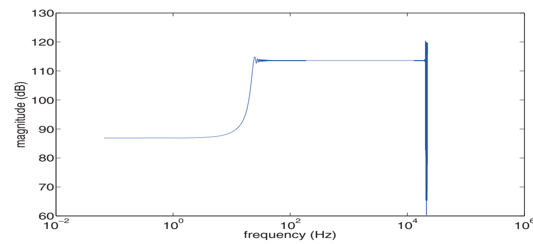
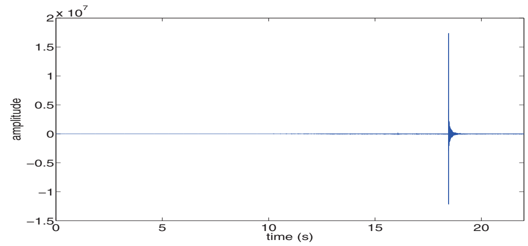
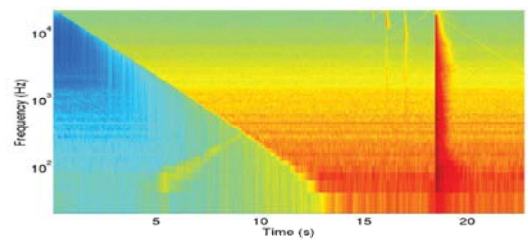


Fig. 7. Magnitude response of inverse filter using modulated exponential sine sweep



(a) impulse response



(b) spectrogram

Fig. 8. Measured impulse response and spectrogram using pre-modulation method

3. CONCLUSION

The sine sweep measurement gives accurate linear impulse response and non-linear harmonics at various orders. Especially for the exponential sine sweep method, it was proved to to offer superior performance over traditional method, with respect to SNR. Its unique clean separation of linear response and harmonic distortion allows the characterizations to be implemented simultaneously.Proper amplitude modulation is needed to accomplish the measurement procedure. The post-modulation scheme results in a clean impulse response and neat layout of linear and non-linear response but requires the modulation operation after measurement. We have introduced a novel modulation scheme which offers a more straight forward and convenient way for the measurement while maintains the accuracy.

4. REFERENCES

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