Distortion estimation and compensation by multi-tone sweep

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ABSTRACT

Audio conferencing systems typically include an echo canceller to remove echo from the loudspeaker that is picked up by the microphone. The echo canceller includes a linear echo canceller for removing linear echos, and a residual echo suppressor for suppressing residual non-linear echos. The residual echo suppressor functions based upon a characterization of the inter-modulation products generated by the audio system, e.g., provided as a distortion map generated using a single-tone sweep at different volumes on the loudspeaker and measuring the distortion at the microphone. Extending this approach to multi-tone input signals has prohibitive memory requirements.

Techniques described herein characterize the inter-modulation performance of a non-linear system by sweeping a multi-tone input signal and mapping the frequency and intensity of the highest input tone to the total output spectral distortion outside the highest input tone. An inter-modulation characterization generated using the techniques has the same memory requirements as a single-tone distortion map and can be used to improve audio quality.

KEYWORDS

- Audio conferencing
- Audio quality
- Non-linear distortion
- Distortion characterization
- Echo canceler
- Multi-tone sweep
BACKGROUND

Signal processing systems, e.g., audio systems, are designed to be linear, or closely so. A strictly linear system is desirable because it produces no distortion, e.g., it maintains the shape of the spectrum of a signal as the signal passes from input to output. However, a strictly linear system is an ideality; all real systems are at least slightly non-linear, especially at high input amplitudes.

![Diagram: Amplitude response of linear and non-linear systems](image)

**Fig. 1: Amplitude response of a strictly linear system (dotted) versus a quasi-linear system (solid)**

Fig. 1 shows an example of the amplitude response of linear and non-linear systems. In a strictly linear system 102 (dotted line), the output amplitude is exactly proportional to input amplitude at all input amplitudes. In a non-linear system 104 (solid line), the output amplitude is almost exactly proportional to the input amplitude, especially at low input amplitudes. At higher input amplitudes, a non-linear system deviates from linearity. A non-linear system that is almost linear at low amplitudes and deviates slightly from linearity at high amplitudes is termed as a quasi-linear system. Real world signal processing systems are almost always quasi-linear.
A strictly linear system reproduces at its output a faithful copy of its input; therefore, the spectra of the input and the output are identical except for a multiplicative gain. Such is not the case for a quasi-linear system, as illustrated in the example shown in Fig. 2.

![Fig. 2: A quasi-linear system produces harmonics of an input tone](image)

In Fig. 2, a high-amplitude single tone (204), represented in the frequency domain by two delta functions at tone location, is input to quasi-linear system 202. The output (206) of the quasi-linear system includes the original tones and harmonics thereof. The harmonics are perceived by the human ear as distortion, known as harmonic distortion.

![Fig. 3: Spectral re-growth in non-linear systems](image)
Another effect of non-linearity is illustrated in Fig. 3, where a high-amplitude input signal (304) that includes closely spaced tones input to a non-linear system results in an output signal (306) that includes several tones that were not present in the input. The output tones are present at the original tones plus integral multiples of the difference between the original tones. The new output tones are known as inter-modulation products. Presence of such tones in the output constitutes a form of audible distortion known as spectral re-growth.

Non-linear distortion, e.g., harmonic distortion, is typically combatted by first characterizing it and then compensating for it based on the characterization. For example, during characterization, a single tone is swept across frequency and amplitude, and the spectral profile of the output is recorded at each input frequency and amplitude value. A distortion map, as produced by the characterization procedure, is measured in advance of deployment of a signal processing system, and is programmed into the system for use during normal operation.

A downside of the distortion map approach is that it only handles single tone distortion and not multi-tone distortion, e.g., inter-modulation distortion. A straightforward extension of the single-tone frequency distortion map, e.g., by using several tones at varying frequencies and amplitudes, is memory intensive to the point of infeasibility.

DESCRIPTION

In audio systems, non-linear distortion often originates from the loudspeaker driver and enclosure vibrations. An audio conferencing system that includes a loudspeaker and microphone, typically includes an echo canceller for removing echo from the loudspeaker that is picked up by the microphone. The echo canceller typically includes a linear echo canceller that removes a linear echo component, and a residual echo suppressor that suppresses the residual echo that mainly includes non-linear distortion. The residual echo is what remains after
the linear echo is removed. The residual echo suppressor functions based upon a characterization of the inter-modulation products generated by the audio conferencing system.

Techniques of this disclosure are based upon the observation that voiced speech comprises a fundamental frequency and multiple harmonics at frequencies that are integer multiples of the fundamental frequency. A distortion map is measured using a multi-tone sweep with a fundamental frequency and multiple harmonics. The frequency and intensity of the highest harmonic is mapped to the microphone distortion present at other, higher frequencies. In this manner, multi-tone distortion is captured by a distortion map with the same memory requirement as a single tone distortion map.

Fig. 4: Characterizing a non-linear system using multi-tone sweep

Fig. 4 illustrates the characterization of a non-linear system, e.g., an audio conferencing system that includes the loudspeaker-microphone acoustic path, using multi-tone sweep. The input signal (404) to the non-linear system comprises tones at a fundamental frequency $f_0$ and harmonics thereof, e.g., $2f_0, 3f_0$, etc., with the highest input tone denoted $nf_0$. The output (406) of the non-linear system includes not only the input tones but also inter-modulation tones, e.g., $(n+1)f_0, (n+2)f_0$, etc.
A map is established between the frequency and amplitude of the highest input tone and the total power of the output distortion products outside of the highest input tone. As the input tones are swept across frequency and amplitude, a map is created between the multi-tone input and the output distortion, thereby characterizing the inter-modulation performance of the non-linear system. The map occupies the same memory as a single-tone characterization of the non-linear system. The distortion map as generated is used to improve audio quality during use of the audio conferencing system.

CONCLUSION

Techniques described herein characterize the inter-modulation performance of a non-linear system by sweeping a multi-tone input signal and mapping the frequency and intensity of the highest input tone to the total output spectral distortion outside the highest input tone. An inter-modulation characterization generated using the techniques has the same memory requirements as a single-tone distortion map and can be used to improve audio quality in an audio conferencing system.