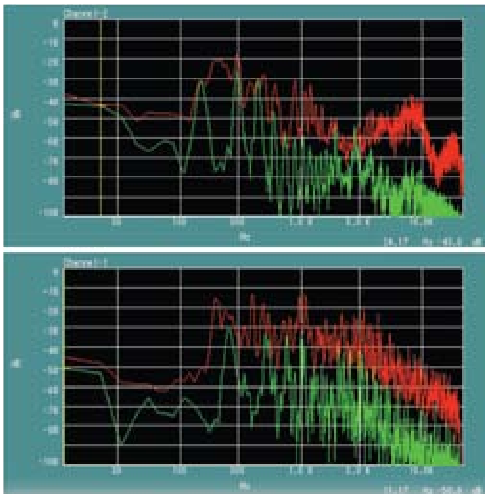
Improved Audio Reproduction with Control Theory

To the discerning listener, sound quality in CDs and other standard digital formats leaves something to be desired. It turns out that this "something" is related to high-frequency signal elements. A new advance based on sampled-data control theory, the YY filter, has overcome this problem with audible advantages!



Fast Fourier transforms (0–20 kHz) of an analog record (top) and CD reproduction (bottom). The green trace is the FFT; the red trace is the peak FFT value over the past 10 seconds. The record exhibits a range that extends well beyond 20 kHz; the CD has a sharp cutoff at 20 kHz. (The traces are not from the same sound.)

Conventional Sound Encoding

The audible range is widely accepted to be limited to 0-20 kHz, and anything beyond is sharply cut (filtered out) by a low-pass filter. This is based on the well-known Whittaker-Shannon sampling theorem; all frequencies beyond the Nyquist cutoff are regarded as noise. However, the Shannon formula is noncausal and hence not directly applicable to sound reconstruction/recovery.

In addition, the high-end frequency (so-called Nyquist frequency) 22.05 kHz (half of the sampling frequency used in digital audio) may not provide sufficient margin against the audible range. Digital filters used today usually cut the frequency components beyond 20 kHz very sharply. But this has the side effect of inducing (1) a large amount of phase distortion (phase error is not considered in the conventional Shannon paradigm); and (2) ringing around 20 kHz due to the sharp-cut characteristic of the filter (Gibbs phenomenon). The latter induces a very "aggressive," sharp, and metallic sound that is likely the main reason for the audiophile's complaints about CD recordings. Undesirable distortions intrude below the Nyquist frequency too.

An Application for Sampled-Data Control Theory

High-frequency components are intersample signals. This observation suggests that modern sampled-data control theory can offer solutions to the problems of sound processing today. Based on recent theoretical results, filters can be designed that optimally interpolate the intersample content (that is, the lost high-frequency components). The optimal continuous-time (analog) performance is recovered.

Commercial Example

The figure below is an example from a mini-disc (MD) (similar format as MP3) player. The horizontal axis is the audio frequency on a linear scale of 0–22 kHz. The top graph shows the frequency response with the MDLP4 standard at 66 kbps. The bottom graph shows the response at the same bit rate with the YY filter implemented. The improved high-frequency response is evident.

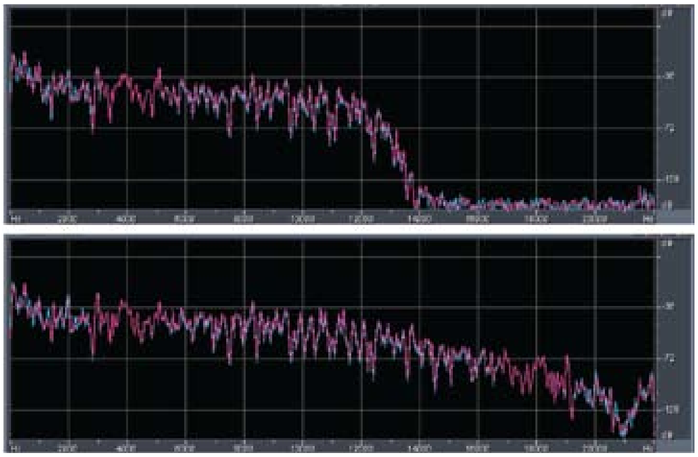


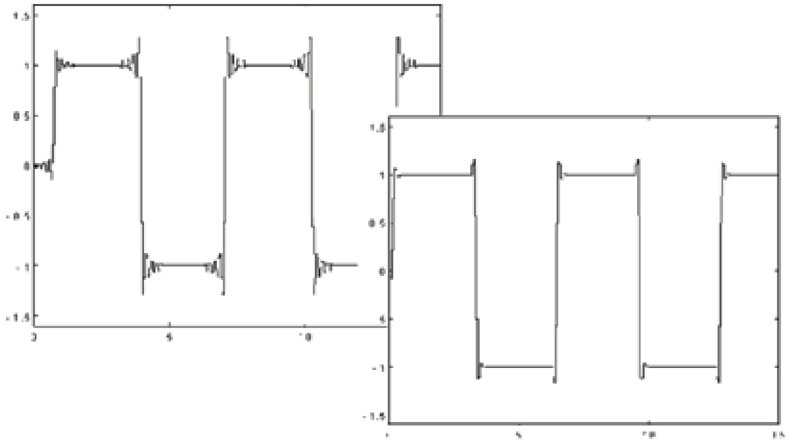
Figure courtesy of Sanyo Corporation.

Contributor: Yutaka Yamamoto, Kyoto University, Japan

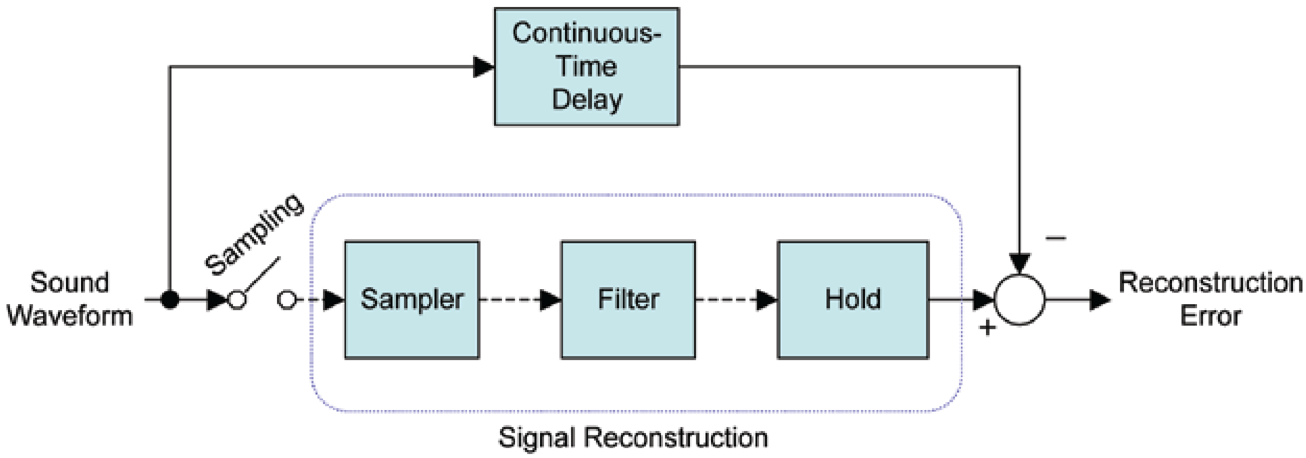
From: *The Impact of Control Technology*, T. Samad and A.M. Annaswamy (eds.), 2011. Available at www.ieeecss.org.

By the Millions!

The YY filter has been implemented in integrated circuits produced by SANYO Semiconductor for expanding the effective range in such devices as CDs, MP3s, mobile phones, digital voice recorders, and car audio systems. The sound quality has proven superior to the original according to the PEAQ (Perceptual Evaluation of Audio Quality) index; the filter enhances the quality by almost 30% for MP3 128 kbps and by over 30% for advanced audio coding (AAC) on average. Cumulative production has reached 16 million chips during the period 2005-2010.



The effect of the YY filter is particularly evident in these reconstructions of a sampled square wave. Conventional reconstruction results in significant high-frequency distortion (the "ringing" observed at the corners of the signal.) The YY filter substantially reduces the distortion.



The YY filter design process mathematically optimizes the filter to ensure that the reconstruction error across a desired frequency range—not determined solely by the Nyquist frequency—is less than a design parameter. This is a sampled-data H_∞ control problem.

Applications to Image Processing

The YY filter can be applied to images as well, as illustrated here. Left image: interpolation via a bicubic filter; right image: interpolation with the YY filter. Visit http://www-ics.acs.i.kyoto-u.ac.jp/~yy/sound.html for high-resolution images.

For further information: Can you hear the difference? Visit http://www-ics.acs.i.kyoto-u.ac.jp/~yy/sound.html.