

AC 2007-104: DIGITAL SIGNAL PROCESSING, THEORY AND PRACTICAL CONSIDERATIONS

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Digital Signal Processing, Theory & Practical Considerations

Abstract

Digital Signal Processing (DSP) is an important and growing subject area within electrical and computer engineering (and also computer science). With the availability of “powerful” tools, software packages and hardware/software systems for use in DSP courses, we need to be careful and use professional judgment as to where/when to use and introduce these teaching aids and tools. The authors have taught both graduate and undergraduate DSP and real-time systems courses, established industry-certified laboratory in the home university where students can do projects without the actual experiments in lecture-only courses. Even “DSP on wheels” concept was used in an attempt to show some practical applications of the subject matter. But students still consider the subject to be highly mathematical and maybe too much on the theoretical side. In this paper we will show some examples of actual classroom projects, homework assignments trying to present a balance between theory and practice. With term projects and papers to be submitted, we have also used electronic (web-based) portfolio system so that project reports and documentation can be uploaded, then instructor can go online and review the work and submit feedback and assessment to the student.

There is also a good collection of textbooks available in the DSP for both undergraduates and graduate students, these are fairly recent texts but because of the inclusion of more simulation type examples maybe theory and underlying principles are being left out. Again the question of balance between theory and practice comes up for discussion among engineering educators. There are a few examples in the paper (mainly using MATLAB and MATHCAD) to show the tradeoffs and importance of understanding the theory and logic for the students before they attempt using computational routines and simulation programs. A discussion needs to be started on the actual time of offering a DSP course in the curriculum (before or after circuits?), how much DSP can/should be included in a freshman engineering type of courses that many schools are starting to offer.

Introduction

For a number of years in our school we have offered both graduate (ECE 555) and undergraduate (ECE 455) courses on digital signal processing, these are each a three-hour lecture-only course. The Oppenheim-Schafer-Buck textbook¹ for the graduate course is widely used in many schools. We use the book by Proakis and Manolakis² as a reference which was also used as an undergraduate text. The book by McClellan-Schafer-Yoder³ is an interesting one for signal processing first approach used in some programs. The book by Smith⁴ is also available online and students can download it for free.

The first author has taught both ECE 455 and 555 courses for the past few years. The experience has shown that students like the course materials especially when examples are worked out in the class, with live demonstrations used when possible. The IEEE

paper⁵ presents more information about the undergraduate course. In the graduate course, students are asked to do a term project on DSP with a written report which can be submitted online using the iWebfolio system. We have found both MATLAB and MATHCAD to be useful software packages for DSP courses, students can use student versions or access them at the Computer-Aided Engineering (CAE) Center in the college.

We will next present DSP theory, course topics, examples using software packages and finally present some conclusions as to the pros and cons of using software tools and the usefulness of having laboratory or term projects as part of the course requirements.

Theory

Signal processing is an important subject area in engineering. A signal can be defined as a function of one or several variables. For example, $f(t)$ is a one-dimensional signal of the variable “ t ” which can represent time. $f(x,y)$ is a two-dimensional signal (e.g., image) of variables x and y . In digital signal processing we study discrete-time or digital signals which can be obtained by sampling a continuous-time signal. For the purpose of discussion in this paper we will follow the notation in reference 1 and use $x[n]$ to represent a digital signal $x(nT)$ where $T = 1/F_s$ is the sampling period (interval) and F_s is the sampling frequency. It is important to distinguish the difference between a discrete-time signal and a digital one (again for more information we ask readers to consult reference 1.)

One important area in DSP is the design/analysis of digital filters, this is also the topic which students find usually more mathematically challenging. Basically a filter is a device or system that will process the input or x to produce output y where some characteristic of the input has been altered by the filter. The so-called input/output relation in the time domain is the LCCDE (linear, constant-coefficient difference equation) representation of the digital filter:

$$\sum_{k=0}^N a_k y[n-k] = \sum_{i=0}^M b_i x[n-i] \quad (1)$$

In the frequency domain one uses the complex (z) frequency variable and finds the system (transfer) function $H(z) = Y(z)/X(z)$. One important input function is the impulse signal $x[n] = \delta[n]$, as a matter of fact any signal can be represented as a sum these impulse functions. When $x = \delta$, we call the output impulse response (IR), $y[n] = h[n]$. Depending on $h[n]$, digital filters are classified as FIR (finite impulse response) or IIR (infinite impulse response). Knowing $h[n]$ we can find the response to any input by the convolution sum:

$$y[n] = x[n] * h[n] = \sum_k x[k]h[n-k], \text{ where } k \text{ is from } -\infty \text{ to } \infty \quad (2)$$

Another way of finding the output is to use the principle of superposition (assuming digital filters to be linear time-invariant systems), $y[n] = y_h[n] + y_p[n]$, where y_h

represents the homogeneous (transient) response and y_p is the particular (forcing) response. Solutions of LCCDEs in both time and frequency domains are discussed and compared. It is shown that there is almost equal amount of work involved in solving the given equation in the time domain or using the z-transform approach. In the transform method one needs to use inverse transformation to find the total response. There may or may not be initial conditions present (ICs).

Design of analog filters is a mature subject, in the design of IIR digital filters one needs to start with these analog filters first. There are a lot of materials that can be covered as part of analog filter design, passive/active filters, classical filters (e.g., Butterworth, Chebyshev, Elliptic, Bessel). Because of time restraint a lot of these topics can not be covered so basic results are presented then course continues in the design of FIR digital filters. It is important to note that at the graduate course students can select a topic and work on it as a term project so they can extend on the materials covered in the class.

Course Topics

In ECE 555, the main topics covered in the course include: Course introduction & overview, discrete-time signals and systems, time/frequency domain representations, linear, time-invariant systems, LCCDEs, eigenvalue (transfer function), frequency selective (ideal) filters, Fourier transforms representation, discrete-time random signals, z-transform and its application in DSP, inverse transform, one-sided, two-sided (bilateral) transforms, solutions of LCCDEs using the z-transform, Nyquist sampling theorem, reconstruction, aliasing distortion, multi-rate signal processing, periodic (impulse) ideal sampling, frequency response of LTI systems, inverse, all-pass, minimum-phase, generalized linear phase systems, implementation and structures of digital filters, block diagram representation, signal flow graphs, , cascade/parallel and direct forms, design of digital filters, IIR, ARMA systems, classical (continuous-time) filters and approximations (Butterworth, Chebyshev, etc), impulse (or step) invariance, bilinear transformation, backward/forward difference approximations, design of FIR filters, MA systems, windowing & truncations, frequency sampling method, computer-aided design methods, digital differentiators, Hilbert transforms, comb filters, optimal approximations, discrete Fourier transforms, DCT, FFT and other algorithms. Again note that students can choose an extension of the topics covered in the class and work on a term project and submit a written report. In addition there are homework assignments, class exams, final exam and computer assignments (using matlab or mathcad.)

Examples

Example 1. When studying systems in time/frequency domain, we use the following IIR system as an example to compare solutions obtained by the two methods.

$$y[n] - 4y[n-1] + 4y[n-2] = x[n] - x[n-1], \quad x[n] = (-1)^n u[n], \quad y[-1] = y[-2] = 0$$

In the time domain, the total response is obtained by the sum of homogeneous and particular responses. After applying zero initial conditions one obtains

$$y[n] = y_h[n] + y_p[n] = A(2)^n + Bn(2)^n + C = (1/9)[7(2)^n + 3n(2)^n + 2(-1)^n]u[n].$$

In the z-domain the solution is obtained by transforming the LCCDE and solving for the transfer function:

$$H(z) = Y(z)/X(z) = z(z-1)/(z-2)^2, Y(z) = X(z)H(z) = z^2(z-1)/[(z+1)(z-2)^2].$$

The inverse transform gives the same answer as $y[n]$ above. Here we discuss the reason why it is important to understand signals/systems in both time and frequency domain. Later in designing IIR filters they can, for example, design different filters based on their pole/zero location an obvious characteristic evident in the frequency domain.

At the same time students can use matlab solution to compare it to the analytical formulation presented above.

```
>> n=0:1:10;
>> B=[1 -1 0];
>> A=[1 -4 4];
>> x=(-1)^n;
>> x=(-1).^n;
>> y=filter(B,A,x)
```

y =

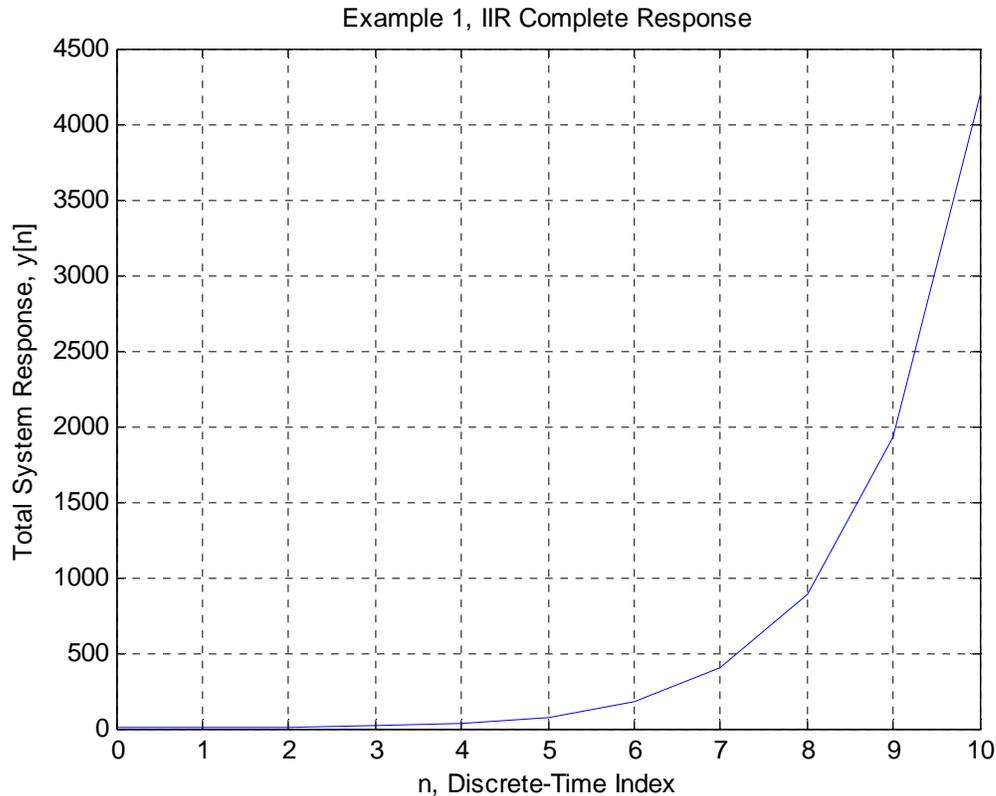
Columns 1 through 8

1 2 6 14 34 78 178 398

Columns 9 through 11

882 1934 4210

```
>> plot(n,y)
>> xlabel('n, Discrete-Time Index')
>> ylabel('Total System Response, y[n]')
>> title('Example 1, IIR Complete Response')
>> grid on
>>
```



Example 2. Here we ask students to design a lowpass digital filter based on a Butterworth approximation and given the following specifications:

Passband cutoff frequency = 3 kHz, attenuation of at least 23 dB for $F \geq 6$ kHz (note that capital letter is used for analog frequency.) We like to use a sampling frequency of 20 kHz.

Although several methods are discussed in the class (in addition to CAD methods, we study backward/forward difference approximation, matched z-transform, impulse/step invariance), here we would like to use bilinear transformation method with pre-warping of frequencies.

Using design formulas discussed in the lecture, it is found that the minimum filter order is $N = 3$, so that normalized analog filter is

$$H(s) = 1/[(s + 1)(s^2 + s + 1)]$$

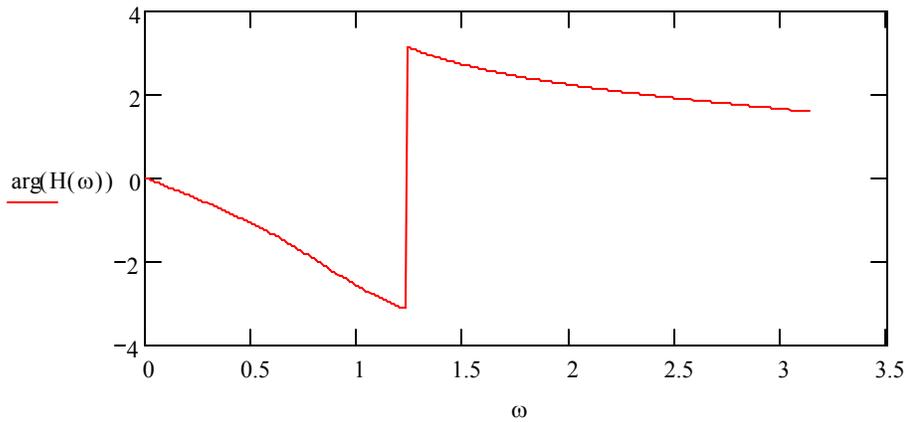
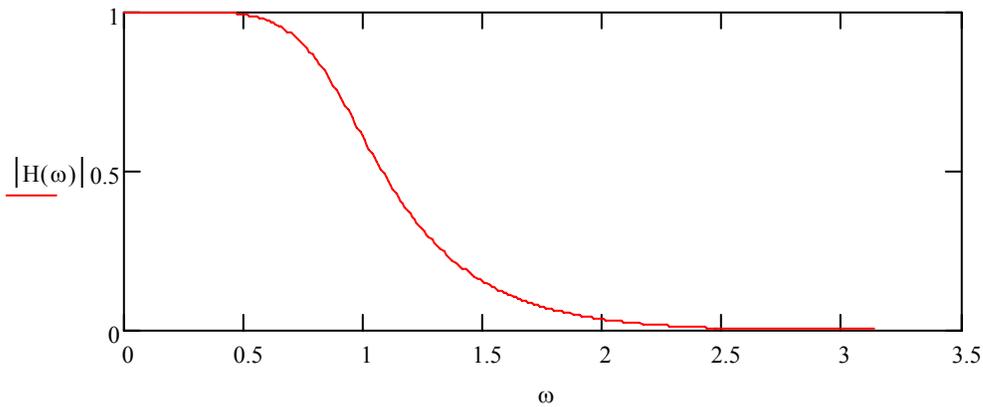
Which can be transformed to obtain the digital design

$$H(z) = (z + 1)^3/[(3z - 1)(7z^2 - 6z + 3)].$$

Note that other analog approximation (e.g., Chebyshev I) can also be used. Here we present simulation results using MATHCAD.

$$\omega := 0, 0.01.. \pi \quad j := \sqrt{-1} \quad z(\omega) := \exp(j \cdot \omega)$$

$$H(\omega) := \frac{(z(\omega) + 1)^3}{[(3 \cdot z(\omega) - 1) \cdot (7 \cdot z(\omega)^2 - 6 \cdot z(\omega) + 3)]}$$



Example 3. In designing FIR filter one approach is to use truncation (windowing) and finite delay of the ideal (desired) impulse response function. For the ideal digital lowpass filter given as $H_d(\omega) = 1$ for $-\omega_c \leq \omega \leq \omega_c$, one gets the desired impulse response

$$h_d[n] = [\omega_c/\pi] \text{Sa}(\omega_c n), \quad -\infty < n < \infty; \quad \text{where sampling function } \text{Sa}(x) = (\sin x)/x.$$

Obviously this filter has ∞ duration (it is also non-causal.) The solution will be to use windowing and finite delay. We will illustrate this design method by designing a digital

FIR differentiator (not an easy analog design or IIR.) For ideal digital differentiator, the desired impulse response is given by

$h_d[n] = \cos(\pi n)/n$, $-\infty < n < \infty$ with $h_d[0] = 0$. We use MATHCAD simulation below to show a couple typical designs using Hanning and Kaiser windows. For Kaiser window with shape parameter $\beta = 5$, we use the paper by Blachman and Mousavinezhad [5] to evaluate the zeroth-order modified Bessel function of the first kind:

$$I_0(x) \approx 1/6 + (1/3) \cosh(x/2) + (1/3) \cosh(\sqrt{3} x/2) + (1/6) \cosh(x).$$

$$\omega := 0, 0.01.. \pi \quad j := \sqrt{-1} \quad n := 1, 2.. 100$$

$$hd(n) := \frac{\cos(\pi \cdot n)}{n}$$

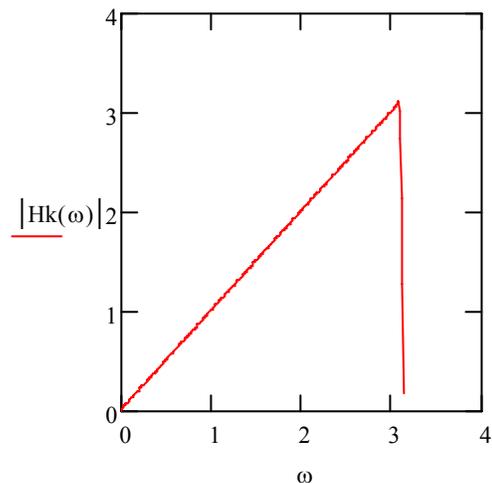
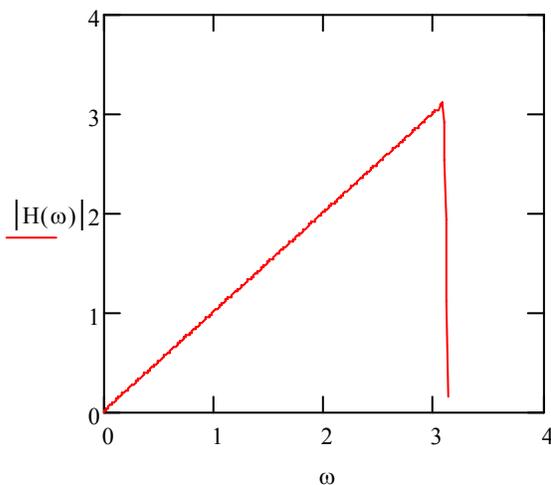
$$w(n) := 0.5 + 0.5 \cdot \cos\left(\pi \cdot \frac{n}{100}\right) \quad \text{Hamming Window}$$

$$H(\omega) := -2 \cdot j \cdot \left[\sum_n (hd(n) \cdot w(n) \cdot \sin(n \cdot \omega)) \right]$$

$$I_0(x) := \frac{1}{6} + \frac{1}{3} \cdot \cosh\left(\frac{x}{2}\right) + \frac{1}{3} \cdot \cosh\left(\sqrt{3} \cdot \frac{x}{2}\right) + \frac{1}{6 \cdot \cosh(x)} \quad \beta := 5$$

$$wk(n) := \frac{I_0\left(\beta \cdot \sqrt{1 - \frac{n^2}{10000}}\right)}{I_0(\beta)}$$

$$Hk(\omega) := -2 \cdot j \cdot \left[\sum_n (hd(n) \cdot wk(n) \cdot \sin(n \cdot \omega)) \right]$$



Real-Time Digital Signal Processing Implementation Considerations

Computational Efficiency

Fast algorithms of digital signal processing become imperative when students work on class projects of real-time applications. Projects are designed that allow students to implement DSP algorithms either on DSP development boards or on general-purpose PCs. When general-purpose PCs are used, high-level programming puts additional computational burden on the processor. It is critical to make the DSP algorithm efficient in order to meet real-time requirements.

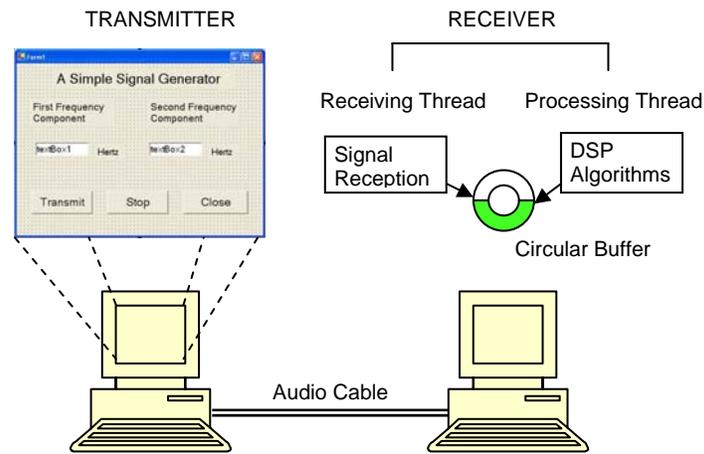


Figure 1. A platform that evaluates computational efficiency of DSP implementation.

For example, one class project is to simulate a signal generator and a frequency analyzer using two PCs (Figure 1). It is programmed in C++. The first PC generates a continuous signal that consists of N frequency components according to user input. The digital signal is fed to the computer audio card that functions as a D/A converter. The audio card has a predetermined sampling rate and outputs an analog waveform of the signal. The signal is transmitted through an audio cable, which is also plugged in the audio input of the other PC. The other PC receives the analog signal through the audio input port and uses the computer audio card as an A/D converter. The receiving PC can perform a series of DSP algorithms on the sampled signal. A simple manipulation of the received data is to perform discrete Fourier transform and detect the N frequency components in the original signal.

There are a few practical issues in this programming task. First, because the sampling rate at the transmitting PC is determined by the selection of the audio card sampling rate, the signal generator has to reject input frequencies that do not satisfied the Nyquist requirement. Secondly, in order not to lose any data at reception, a multi-threaded program is necessary at the receiving PC. One thread, called receiving thread, takes the data in from the audio card, while the other thread, called processing thread, performs Fourier transform and detects the N largest peaks with their corresponding frequencies.

These two threads share a common circular buffer with its associated synchronization mechanism. When the DSP algorithms are computationally heavy in the processing thread, it may not be able to finish processing the data before new data flushes in from the audio input port.

The students are made aware of this phenomenon of data loss due to inefficient DSP algorithms. And, they are encouraged to make modifications to the algorithms so that the data processing is completed before the circular buffer would overflow. A straightforward solution to this problem is to implement a fast Fourier transform algorithm. Students can try various FFT algorithms that include decimation-in-time and decimation-in-frequency FFT algorithm, and with various bit orders in the FFT butterfly graph¹.

Digitization Effects and System Stability

The digitization effects come in the forms of sampling aliasing and quantization error. The sampling aliasing can be demonstrated in the above example of the class project. The quantization error can be classified as signal quantization errors and filter coefficient quantization errors. In DPS implementations, the arithmetic roundoff noise and the overflow effect should also be considered.

After sampling, the discrete-time signal $x(nT)$ is encoded using B-bit wordlength to obtain the digital signal $x(n)$. We assume that $-1 \leq x(n) < 1$, thus a dynamic range of 2. Since the quantizer employs B bits, the number of quantization levels is 2^B . The quantization resolution, i.e. the spacing between two successive quantization levels, is

$$\Delta = 2/2^B = 2^{-B+1}$$

The sampled value $x(nT)$ is rounded to the nearest level of a B-bit word. The quantization error $e(n)$ can be expressed as

$$e(n) = x(n) - x(nT)$$

It is clear that

$$|e(n)| \leq \Delta/2$$

The quantized signal can be expressed as

$$x(n) = x(nT) + e(n)$$

For an arbitrary signal with fine quantization (B is large), the quantization error $e(n)$ is assumed to be uncorrelated with $x(n)$, and is a random noise that is uniformly distributed in the interval $[-\Delta/2, \Delta/2]$. Therefore, $e(n)$ is zero mean with variance $\sigma_e^2 = 2^{-2B}/3$.

Therefore, the signal-to-quantization-noise-ratio (SQNR) can be expressed in dB as

$$\text{SQNR} = 10 \log_{10}(\sigma_x^2/\sigma_e^2) = 4.77 + 6.02B + 10 \log_{10}\sigma_x^2$$

Where, σ_x^2 denotes the average signal power. This equation indicates that for each additional bit used, the quantizer provides about 6-dB gain.

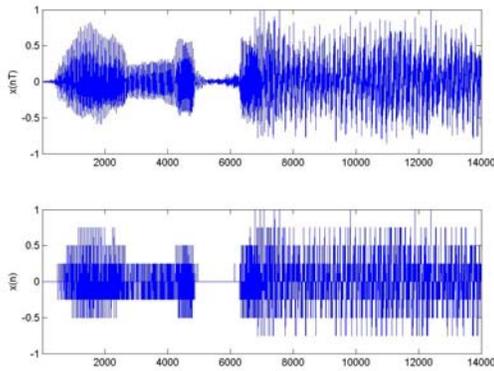


Figure 2. MATLAB example of quantization effect.

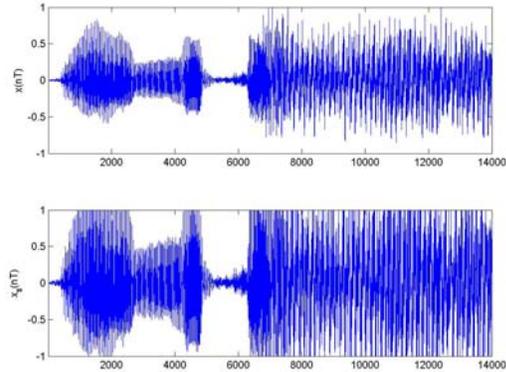


Figure 3. MATLAB example of overflow (saturation) effect.

Effects of signal quantization may be subjectively evaluated by observing and listening to the quantized audio signal. In a classroom demonstration of the quantization effects, we use MATLAB to read in a song wave and play it back on the speaker. The original audio signal, $x(nT)$, is quantized with different resolutions. The quantized audio signal, $x(n)$, is also played back on the speaker to compare with the original one. Fig. 2 shows portions of the signal waveforms of the original audio signal $x(nT)$ and the quantized audio signal $x(n)$. In this figure, the quantizer has $B = 3$ bits, and $\Delta = 2^{-B+1} = 0.25$. With the same original audio signal, we can also demonstrate the overflow or saturation effect in DSP implementations. The saturated signal waveform is also played back using MATLAB on the speaker, and compared with the original audio signal. Fig. 3 shows the original audio waveform and the saturated waveform. The graphs and audio demonstrations provide students with a good understanding of the quantization and saturation effects.

Another DSP implementation consideration is the filter coefficient quantization effect. The filter coefficients of the digital filter determined by a filter design package such as MATLAB are usually represented using the floating-point format. When implementing a digital filter, the filter coefficients have to be quantized for a given fixed-point processor. Therefore, the performance of the fixed-point digital filter will be different from its design specification.

The coefficient quantization effects become more significant when tighter specifications are used, especially for IIR filters. Coefficient quantization can cause serious problems if the poles of designed IIR filters are too close to the unit circle. This is because those poles may move outside the unit circle due to coefficient quantization, resulting in an

unstable implementation. Such undesirable effects are far more pronounced in high-order systems.

The coefficient quantization is also affected by the structures used for the implementation of digital filters. For example, the direct-form implementation of IIR filters is more sensitive to coefficient quantization than the cascade structure consisting of sections of first- or second-order IIR filters⁶. Real-time DSP application examples on an unstable system that results from coefficient quantization errors are provided in class.

Conclusions

Balancing theory and practice is important in many engineering subjects, especially those that have a lot of mathematical concepts and abstractions. The study of digital signal processing and its application is vital to the curriculum of electrical and computer engineering. Within the related courses, we have provided students with software packages for DSP demonstration and simulations, and with hardware/software platforms for DSP implementation on small projects. These tools have proved to be interesting and useful for the students to grasp fundamental knowledge in DSP. We have shown some actual classroom examples and homework assignments in both theory and practice. A laboratory component in digital signal processing is highly recommended for senior classes. Our university has a relatively long history of offering classes in DSP at both undergraduate and graduate level with emphasis on class projects and laboratory hands-on experience. We believe that it is important to introduce modern tools and software packages at the right time, right place.

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