

has approximately the same response as the B-weighting filter with the exception that it has about a 4 dB peak in its response between 3 and 4 kHz. The use of all of these filters is somewhat questionable because measurements made with them do not exactly correlate with psychoacoustic tests. The A-weighting filter has been used for so long to document so many noise measurements that it is almost considered a standard. For this reason, most noise measurements are specified in dBA.

## 1.12 Audio Test Signals

The sine wave is the “king of the test signals.” It is the only test signal in nature which is preserved in shape by all linear systems. It is used to measure frequency response, distortion, and overload characteristics of electronic circuits, microphones, and loudspeakers. If a pure sine wave is analyzed with a Fourier transform, its spectrum would be found to contain only one frequency component. Analog function generators synthesize sine waves by passing a triangle wave through a nonlinear diode wave shaping circuit to shape the triangle wave into a sine wave. If the signal is analyzed with a spectrum analyzer, it would be found to contain frequency components at harmonic frequencies of the fundamental. These harmonics are called distortion components or harmonic distortion.

The purest sine waves are generated by low distortion analog oscillators. These circuits are feedback amplifiers designed to have positive feedback at the frequency of oscillation. To minimize distortion, the amplifier loop-gain must be exactly unity. This can be achieved with an automatic gain control circuit which detects the amplitude of the oscillations and generates a control voltage to adjust the loop gain. If the amplitude of the oscillations increases, the gain is reduced. If the amplitude decreases, the gain is increased. Low-distortion oscillators are commonly used when it is desired to measure the distortion generated in circuits such as audio power amplifiers. For general purpose testing, the function generator is an acceptable sine wave source.

The square wave is a second periodic type of test signal that is used for audio frequency tests. It is used to measure what is called the “transient response” of amplifier circuits, filters, etc. The square wave is rarely used in loudspeaker testing because the phase and amplitude characteristics of loudspeakers do not preserve the square wave shape well enough to be able to interpret the results. The reason the square wave makes such a good test signal is that it contains a fundamental frequency component and harmonics which must be reproduced precisely with correct amplitude and phase if the signal shape is to be preserved. By observing the square-wave response of an amplifier on an oscilloscope, both the amplitude and the phase response can be judged without changing the frequency of the signal. Some of these effects at low frequencies are illustrated in Fig. 1.7.

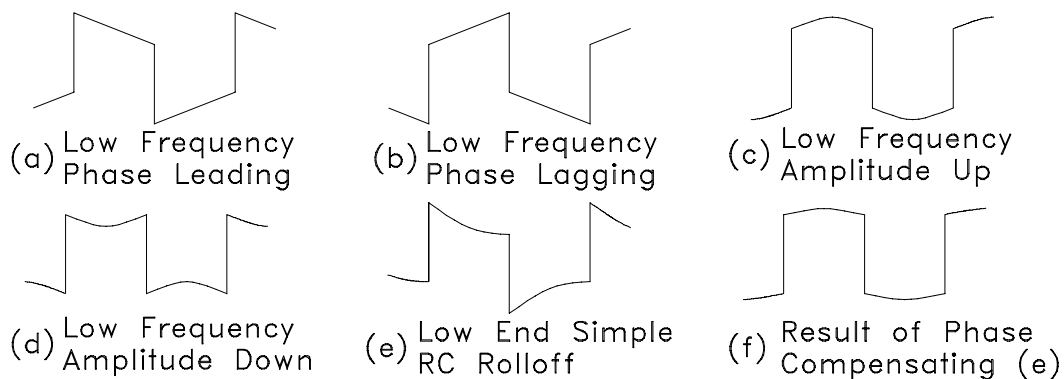


Figure 1.7: Effects of low-frequency gain and phase on square-wave response.

Amplifiers that do not have sufficient stability margin can exhibit a square wave response that exhibits

high-frequency ringing, i.e. a damped sinusoidal oscillation is generated each time the square wave switches states. This is a very undesirable condition, for it indicates that the amplifier can break into sustained high-frequency oscillations if some parameter in the circuit is unavoidably changed.

A random signal that is used in testing loudspeakers is called pink noise. Pink noise is generated from white noise which is a random noise that exists to some extent in all electronic circuits. For example, white noise is generated by all resistors, BJTs, JFETs, MOSFETs, vacuum tubes, signal diodes, Zener diodes, etc. The basic mechanism that generates it is the random flow of current carriers in the devices. That is, current flow is not continuous but consists of discrete charges which flow randomly to form the total current. The random component of the current flow normally exhibits the characteristics of white noise.

With white light as an optical analog, white noise by definition has constant power per unit frequency. That is, it has the same power between 100 Hz and 200 Hz as it has between 1 kHz and 1.1 kHz. Another description is that white noise exhibits a flat spectral density. That is, a plot of the power per unit frequency versus frequency has a zero or flat slope. One method that has been used to generate white noise is to amplify the noise voltage produced by a pn junction that is biased in its Zener breakdown region.

Pink noise is generated from white noise by passing it through a pink-noise filter. The gain versus frequency of a pink-noise filter has a slope of  $-10$  dB/dec over the frequency band of interest. The optical analog to pink noise is pink light which has more power at the longer wavelengths, i.e. at the lower frequencies.

The spectral density of a signal is the mean-square voltage per unit bandwidth, where the mean-square voltage is the square of the rms voltage. For pink noise, the spectral density is written

$$S(f) = \frac{V_0^2}{f} \text{ V}^2/\text{Hz} \quad (1.11)$$

where  $V_0$  is a constant having units of volts. The mean-square voltage in any frequency interval is obtained by integrating this function over the interval and taking the square root. It is given by

$$V_{rms} = V_0 \sqrt{\int_{f_1}^{f_2} \frac{df}{f}} = V_0 \sqrt{\ln \left( \frac{f_2}{f_1} \right)} \quad (1.12)$$

It follows from this equation that pink noise has equal voltage per octave, per decade, per one-third octave, etc. For example, pink noise has the same voltage between 100 Hz and 200 Hz as it does between 1 kHz and 2 kHz.

In testing loudspeakers, pink noise is commonly used to measure the frequency response with the aid of an instrument called a real-time spectrum analyzer. This device typically contains 24 third-octave band-pass filters which cover the audio frequency band. There is a rectifier at the output of each filter. The voltage outputs of the rectifiers are displayed as a function of frequency on a CRT screen or on an LED matrix. If pure pink noise is applied to the spectrum analyzer, equal voltage outputs from each rectifier are generated. This causes a flat frequency response to be displayed. If the pink noise is applied to a loudspeaker and the output of the loudspeaker is picked up by a microphone which drives the real-time analyzer, the frequency response displayed corresponds to that of the loudspeaker and microphone in combination. If the microphone is assumed to be perfect, the frequency response corresponds to that of the loudspeaker.

The combination of a real-time analyzer, a pink-noise generator, and a calibrated microphone makes a very powerful development tool for loudspeaker system design. In crossover network design, for example, inductors, capacitors, and resistors must be connected to the loudspeaker drivers to properly divide the audio signal between the drivers and to optimize the frequency response of the system. The experimental part of crossover network design is greatly simplified if the frequency response of the loudspeaker system can be observed in real time as the changes are made. Another application of pink noise and a real-time spectrum analyzer is in setting up a graphic equalizer for a loudspeaker system in an auditorium.

### 1.13 Problems

1. (a) What is the number of  $1/3$  octaves (whole number and fraction) in a decade? [9.97] (b) How many octaves are in a decade? [3.32]

2. (a) Calculate the 5th and 6th ISO preferred center frequencies above 1 kHz for a 1/3-octave band-pass measuring filter. [3.18 kHz, 4 kHz] (b) How many 1/6-octave ISO frequencies are in the 20 Hz to 20 kHz band? [59.8]
3. (a) To the nearest whole number, how many octaves are in the frequency band from 20 Hz to 20 kHz? [10] (b) To the nearest whole number, how many 1/3-octaves are in the frequency band from 20 Hz to 20 kHz? [30]
4. (a) A 1/3-octave band-pass filter has a center frequency of 8 kHz. What are its lower and upper  $-3$  dB cutoff frequencies? [7.13 kHz, 8.98 kHz] (b) An octave band-pass filter has a center frequency of 4 kHz. What are its lower and upper  $-3$  dB frequencies? [2.83 kHz, 5.66 kHz]
5. Find the rms value of the following pressure functions: (a)  $p(t) = p_1 \cos \omega_1 t + p_1 \sin \omega_1 t$  [ $p_1$ ], (b)  $p(t) = p_1 \cos \omega_1 t + p_2 \cos \omega_2 t$ ,  $\omega_1 \neq \omega_2$   $[[p_1^2 + p_2^2] / 2]^{1/2}$ , (c)  $p(t) = p_1 \cos \omega_1 t + p_2 \sin(\omega_1 t + \pi/4)$   $[[p_1^2 + \sqrt{2}p_1p_2 + p_2^2] / 2]^{1/2}$
6. What fraction of the atmospheric pressure is the rms acoustic pressure in a sound wave with an *SPL* of (a) 40 dB, (b) 90 dB? [ $1.97 \times 10^{-8}$ ,  $6.24 \times 10^{-6}$ ]
7. (a) What is the rms acoustic pressure in a sound wave which has an *SPL* of 110 dB? [6.33 Pa] (b) If the acoustic pressure in the wave varies sinusoidally with time, what is the peak acoustic pressure? [8.94 Pa] (c) If the acoustic pressure in the wave varies as a square wave with time, what is the peak acoustic pressure? [6.33 Pa]
8. (a) What rms voltage is required across an  $8 \Omega$  load if 10 W of average power is to be dissipated? [8.94 V rms] (b) If the voltage is sinusoidal, what are the peak voltage and the peak power? [12.6 V, 20 W]
9. The rms or root-mean-square value of a function of time is defined as the square root of the average value of the square of the variable. For example, the rms value of a voltage  $v(t)$  is given by  $v_{rms} = \sqrt{\langle v(t)^2 \rangle}$ , where the symbols  $\langle \cdot \rangle$  denote a time average. Let  $v(t) = V_1 \sin 2\pi f_1 t$  be the voltage across a resistor  $R$ . (a) Calculate the rms voltage across the resistor. [ $V_1/\sqrt{2}$ ], (b) The instantaneous power dissipated in the resistor is given by  $P(t) = v(t)^2/R$ . Calculate the average value of  $P(t)$ , i.e. calculate  $\langle P(t) \rangle$ . [ $V_1^2/2R$ ], (c) Using the definition of the rms value of a variable, calculate the rms value of the power  $P(t)$ , i.e. calculate  $\sqrt{\langle P(t)^2 \rangle}$ . [ $0.6124V_1^2/R$ ], (d) If the average sine wave power dissipated in an  $8 \Omega$  resistor is 100 W, what are the peak and rms values of the voltage across the resistor? [40 V, 28.28 V] What is the rms value of the power? [122.5 W] Note: Although it is correct to speak of rms voltage, current, pressure, etc., the concept of rms power is meaningless. Despite this, advertisements use the term rms power when they really mean average power.
10. The *SPL* for each of four different sounds is 70 dB, 72 dB, 62 dB, and 75 dB. What is the total *SPL* due to all of these sounds? [77.7 dB]
11. (a) Use the Fletcher Munsen curves to determine the phon level of a 90 dB sound wave at 10 kHz? [about 80 phons] (b) What is the sone level of the sound wave? [16 sones]
12. What is the total phon level of two tones, one with a frequency of 100 Hz and an unweighted *SPL* of 80 dB and the other with a frequency of 5 kHz and an unweighted *SPL* of 70 dB? [75 phons + 70 phons = 76.2 phons]
13. (a) Use the Fletcher Munsen curves to determine the unweighted *SPL* of a 100 Hz sound wave having a sone level of 12.3. [about 80 dB] (b) What is the A-weighted *SPL*? [59 dBA]

14. The phon level for each of four different sounds is 68, 73, 60, and 70 phons. What is the total sone level due to all of these sounds? [11.9 sones]
15. (a) A 100 Hz sound wave has an  $SPL$  of 90 dB as measured with a sound level meter having a flat response. Use the A weighting frequency response graph in Fig. 1.6 to determine the  $SPL$  on an A-weighted sound level meter. [about 69 dBA] (b) If a 100 Hz sound wave has an A-weighted  $SPL$  of 90 dBA, what would be the  $SPL$  on an unweighted sound level meter? [about 111 dB] (c) What is the relative amplitude response of the A-weighting filter at a frequency of 80 Hz? [about  $-24$  dB] (d) An A-weighted sound level meter has a reading of 50 dBA for a 400 Hz tone. What is the unweighted  $SPL$ ? [about 56.2 dB]
16. (a) What is the total phon level of two sound waves, one with a frequency of 200 Hz and an unweighted  $SPL$  of 60 dB and the other with a frequency of 2 kHz and an unweighted  $SPL$  of 50 dB? [50 phons + 50 phons = 53 phons] (b) What is the total loudness in phons of a 40 dB 200 Hz tone plus a 70 dB 50 Hz tone? [20 phons + 35 phons = 35.1 phons] What is the combined  $SPL$  of the two tones? [40 dB + 70 dB = 70 dB]
17. (a) A sone level of 24 corresponds to what phon level? [85.85 phons] (b) If the frequency is 200 Hz, what unweighted  $SPL$  would it correspond to? [about the same] (c) To what A-weighted  $SPL$ ? [73.85 dBA]
18. A method for measuring the loudness level of an audio signal that involves filtering the signal with 10 band-pass filters is described in Section 1.11. Construct a block diagram for the loudness measuring system and label the function of each block in the diagram.
19. Pink noise has a spectral density of the form  $S(f) = V_0^2/f \text{ V}^2/\text{Hz}$ , where  $V_0$  is a constant. The total voltage in a frequency band is obtained by integrating  $S(f)$  over that band and taking the square root. (a) Obtain the expression for the voltage in pink noise in the band from  $f_1$  to  $f_2$ . [ $V = V_0\sqrt{\ln(f_2/f_1)} \text{ V}$ ], (b) If  $f_2 = 2f_1$ , show that the voltage is independent of  $f_1$ . [ $V = V_0\sqrt{\ln 2} \text{ V}$ ]
20. The voltage spectrum of a signal is the square root of the spectral density defined in problem 19. It has the units  $\text{V}/\sqrt{\text{Hz}}$ . On a dB-log plot, sketch the plot of the voltage spectrum for (a) White noise which has a constant power per unit bandwidth. [a straight line of zero slope] (b) Pink noise which has a constant power per octave (or any fraction of an octave). [a straight line with a slope of  $-3$  dB/octave]