

Chapter 4

Instrumentation

Acoustics is an ancient science. In the fifth century BC, Pythagoras made the science of musical tones into an entire philosophy. In renaissance times Galileo and Descartes developed the mathematics of musical tones, and Isaac Newton tried (but failed) to calculate the speed of sound in air. The nineteenth century saw the beginning of truly serious study of human hearing—the anatomy, the physiology, and the psychology. Herman von Helmholtz led the way.

In the twentieth century the study of acoustics got two tremendous boosts. The first boost arrived in the first half of the century with the introduction of electronics and the invention of acoustical instrumentation. For the first time, scientists had a tool for studying sound that was fast enough to keep up with the full frequency range of sound itself. The second boost arrived in the second half of the century with the widespread availability of computers and digital signal processing. After these two revolutions, nothing in the ancient science of acoustics will ever be the same again.

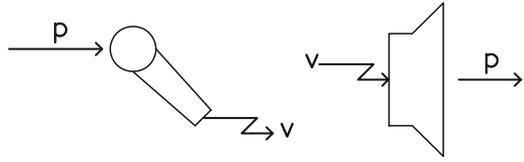
This chapter is about electronic instrumentation. It deals with the subject of transducers and with four instruments: the oscilloscope, the spectrum analyzer, the frequency counter, and the function generator.

4.1 Transducers

A transducer is a device that converts a signal from one form to another. If you want to make an audio recording, you use a microphone. A microphone is a transducer. As indicated by Fig. 4.1, it converts a signal from the acoustical domain, where it is a pressure waveform transmitted through the air, to the electrical domain, where it is a voltage waveform transmitted through wires.

To do the reverse process, converting an electrical signal into an acoustical pressure waveform in the air, you use another transducer—a loudspeaker or a set of headphones.

Fig. 4.1 A microphone converts a signal from an acoustical pressure wave (p) to an electrical voltage (v). A loudspeaker does the reverse



The microphone and loudspeaker are known as analog devices. They are called so because the output of the device is analogous to the input. For instance, if a microphone receives a sound pressure waveform of a particular shape, then the output from the microphone ought to be a voltage waveform that preserves the details of that shape at every instant in time. If the output does not exactly represent those details, then the microphone has distorted the signal.

A well-behaved transducer that does not distort the signal is *linear*. In a linear transducer, a change in the input to the devices causes a proportional change in the output. If from one instant of time to the next the input changes by a factor of 1.27 (becomes 1.27 times larger), then the output must change by a factor of 1.27. If it changes by a factor of 1.26 instead of 1.27 there is distortion.

Linearity can be shown on a graph that describes the relationship between the input and the output. The graph must be a straight line as in Fig. 4.2a. That is the meaning of the word “linear.” The idea of linearity also normally assumes that the straight line goes through the origin so that the output is zero when the input is zero. The operation of microphones, loudspeakers, and other transducers is further discussed in Chap. 16.

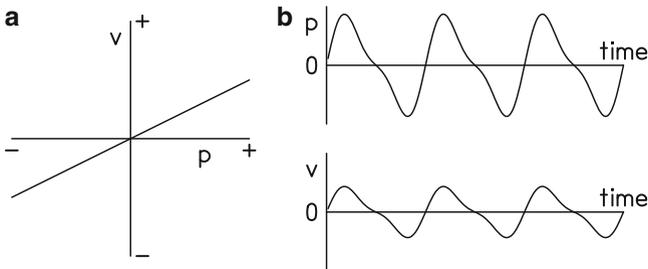


Fig. 4.2 (a) The input/output relationship of a linear transducer is a straight line. For a microphone, the output in volts (v) is linearly related to the input in pressure units (p). Positive and negative axes are shown. (b) The input pressure waveform is transduced by the microphone into an analogous voltage waveform. Because the slope of the line in (a) is shallow, the voltage (v) in part (b) is shown smaller than the pressure (p), but the shape of the pressure waveform is preserved in the voltage waveform

4.2 The Oscilloscope

The oscilloscope (or “scope”) is an instrument that displays waveforms as functions of time. The horizontal axis of the display represents time and the vertical axis represents a voltage. The voltage may come from a microphone, so that in the end the oscilloscope can show a sound wave and its dependence on time.

There are two types of ‘scopes available, analog and digital. The analog ‘scope may use a cathode ray tube (CRT) for the display, as shown in Fig. 4.3. CRT displays were formerly the standard displays in television sets and computer monitors. The digital ‘scope uses either a CRT display or a liquid crystal display (LCD). LCD screens are also found in laptop computers, ipads, graphing calculators, and cell phones.

4.2.1 Analog ‘Scope and CRT Display

A “cathode ray” is actually a beam of electrons shot out from an electron gun toward the screen in the front of the tube. The screen is coated with a fluorescent material that glows briefly when it is hit with a high-speed electron. The electron beam from the gun speeds down the neck of the tube and hits the screen directly in the center. Then if you look at the screen you will see a single small dot, right in the middle.

To make a useful picture we need to move the dot from left to right and up and down on the screen. We need to move it so rapidly that we don’t see a moving dot—we see a picture instead. The dot is moved electronically by horizontal and vertical deflection mechanisms that deflect the electron beam from its straight-line path. This is done using the charged properties of the electron. Deflection plates are placed in pairs—top and bottom, and left and right—within the CRT. These deflection plates are given either a positive or negative charge to deflect the electron in the desired direction. The oscilloscope gives the user great control over the way the dot is moved.

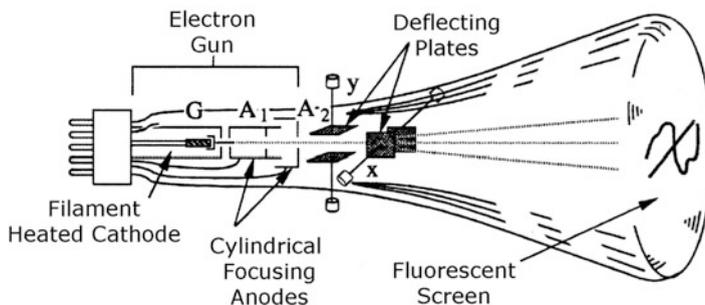


Fig. 4.3 A cathode-ray tube is the display for ‘scopes without digital memory

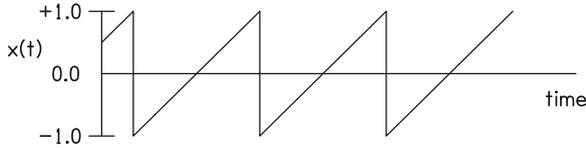


Fig. 4.4 The sawtooth waveform always increases in the sense that it never spends any time decreasing. When it controls the horizontal position of the dot, the dot always moves from *left* to *right*. A dot controlled by the sawtooth wave shown here would start to the *right of center*, about half way to the *right-hand edge*. It would move to the *right*, snap back to the *left-hand edge* and move to the *right* again three times

Horizontal Deflection of the Analog Oscilloscope We would like the analog oscilloscope to draw a waveform as a function of time. That means that the horizontal motion of the dot must sweep from left to right proportional to time. The way to make this happen is to use a sawtooth waveform for the horizontal deflection circuit. Figure 4.4 shows this waveform always moving from a value of -1 (left) to a value of $+1$ (right). The sawtooth is a straight-line function of time, and so the horizontal motion is proportional to time. There are brief instants when the sawtooth jumps back from $+1$ to -1 , but these jumps take place almost instantaneously and they leave no trace on the screen. The rate of the sawtooth, the number of sawtooth cycles per second, is something that the user can freely adjust to get a good display. To see a signal that has a high frequency requires that the sawtooth also be rapid. That is a good reason for using CRTs with deflection plates—the fastest known way to move an electron beam.

Vertical Deflection of the Analog Oscilloscope The vertical deflection of the dot on the screen in the analog 'scope is controlled by the signal that we want to display. For instance, if we want to examine the sound radiation of a tuning fork, we put a microphone near the fork to get an analogous voltage. Then this voltage goes to the *vertical amplifier* of the oscilloscope to adjust its amplitude to a convenient value. The output is thus analogous to the input, hence the name analog oscilloscope. In the end, the 'scope displays the microphone signal (y-axis) as a function of time (x-axis).

4.2.2 Digital 'Scopes and Liquid Crystal Displays

The difference between analog and digital oscilloscopes is that a digital 'scope “digitizes” the input and stores it in digital memory before it is displayed. A digital scope has a converter, like the sound card on a computer, to convert analog signals to digital signals. Once the signal is in digital form it can easily be manipulated and displayed. Because the digital signal is stored in the oscilloscope's memory the display doesn't have to be as fast as the display in an analog 'scope. The digital

display doesn't have to keep up with the signal in real time. This gives the digital 'scope display options such as liquid crystal displays.

Just as cathode-ray tubes are being replaced by liquid crystal and plasma displays in televisions, so too CRTs are being replaced by LCDs in oscilloscopes. In contrast to the analog CRT, which draws continuous line, the LCD uses a series of discrete pixels. Each pixel is created from a liquid crystal. A liquid crystal is made from molecules that are twisted unless an electric signal is applied to them. Applying an electric signal untwists the molecules. The LCD screen is made with polarizing glass such that when the crystals are twisted they let the light through, and when they are untwisted they block the illuminating light. In this way the LCD screen creates an image by using the electric signal from the input source to determine which pixels to transmit light and which pixels to block out light.

4.2.3 Beyond the Basic Oscilloscope

Important refinements to the basic oscilloscope include the following:

- (a) *Triggered sweep*: A circuit that synchronizes the start of the horizontal sweep with the waveform being displayed. With triggered sweep, subsequent traces of a periodic waveform are identical on the screen. That's important because, at any one time, there are many traces visible on the screen. If the traces are not synchronized, the image is a jumble.
- (b) *Dual trace*: The ability to display two different waveforms on the same screen at the same time. The two waveforms are drawn simultaneously, causing them to be perfectly aligned in time. The dual-trace feature allows the user to compare waveforms. For instance, one can compare the input and the output of a device to determine the effect of the device.
- (c) *Digital memory*: The ability to store a waveform. In a conventional analog 'scope, when the signal dies away the amplitude on the display dies away as well. How could it do anything else? But suppose that we were able to capture a waveform in memory and keep on playing it back to the vertical deflection circuit. Then we could capture a transient event, like a drum beat, and watch it for as long as we want. That's a big advantage of the digital 'scope.

4.3 The Spectrum Analyzer

The spectrum analyzer is like the oscilloscope in that it displays a picture on a screen, but that is the end of the resemblance. The spectrum analyzer displays amplitudes as a function of frequency. What a difference! In the oscilloscope the horizontal axis is time; in the spectrum analyzer it is frequency. In the oscilloscope

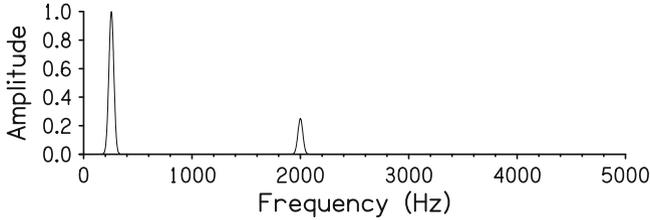


Fig. 4.5 If a tuning fork has a main mode at 256 Hz and a clang mode at 1,997 Hz, then the spectrum analyzer will display two peaks. The heights of the peaks indicate the relative amplitudes in those two modes

the vertical axis is the signal itself; in the spectrum analyzer it is the amplitude of the component whose frequency corresponds to the value on the horizontal axis.

Obviously the spectrum analyzer is just what we need if we want to analyze a signal into its sine wave components. For instance, if we put in a signal from a tuning fork shortly after it is struck, then the spectrum analyzer will indicate the presence of amplitude at the main frequency and at the frequency of the clang mode. Ideally the display would be two vertical lines like Fig. 3.6. Instead, these lines always have a certain width causing the vertical spikes to become peaks, as shown in Fig. 4.5.

The analysis performed by the spectrum analyzer is far more complicated than simply displaying the signal on an oscilloscope. It takes a certain amount of time to do the analysis. In a swept-frequency analyzer, a trace goes from left to right on the screen as the instrument makes its analysis, frequency by frequency. The analysis is not complete until the trace reaches the right-hand edge. The signal has to last for the entire duration of the analysis. If the signal changes during the course of analysis, the analysis will be inaccurate. Therefore, the swept-frequency analyzer would not really be appropriate to study a decaying signal like the tone of a tuning fork. Once again, digital electronics can help. A digital spectrum analyzer can store a brief signal in memory and perform the frequency analysis later. Alternatively, the digital spectrum analyzer can make successive analyses of a long signal, refining its measurement on each pass.

The amplitude displayed on the vertical axis of the CRT display or LCD is not exactly like the display shown in Fig. 4.5. Instead, it is normally displayed in decibels. The decibel transformation of amplitude allows the analyzer to display components of greatly different amplitude all on the same graph on the screen. We will study this decibel transformation in Chap. 10.

4.4 The Frequency Counter

The frequency counter does not have a screen like an oscilloscope. It just has a numerical readout with half a dozen digits. The readout indicates the frequency (in Hz) of the signal that is put into the counter. An obvious problem is that a signal may have many different frequencies—more about that later (Fig. 4.6).

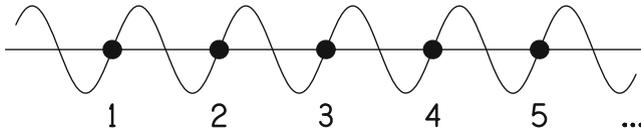


Fig. 4.6 The frequency counter counts positive-going zero crossings in a signal that comes through the gate

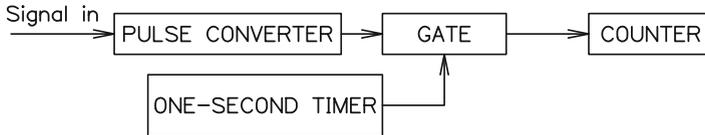


Fig. 4.7 Block diagram showing the functional components of a frequency counter

The frequency counter works by mindlessly counting the occurrence of a particular feature in the signal voltage. It is common to count positive-going zero crossings. You know that a sine signal has one positive-going zero crossing per cycle. So does a sawtooth signal (Fig. 4.4). Therefore, by counting positive-going zero crossings, the counter is counting the number of cycles. The number of cycles is displayed on the numerical readout. It counts 001, 002, 003, 004, . . . As shown in Fig. 4.7, the next ingredient in the counter is an electronic gate that tells the counter when to count. The gate is precisely 1 s long. Therefore, the counter reads out the number of cycles that occur in 1 s. Wow! That is exactly what we mean by frequency. Now we have a frequency counter.

When we use the frequency counter, we are making several assumptions. We assume that the signal does not change during the 1-s gate interval required to count cycles. We also assume that there is only one positive-going zero crossing per cycle. If the signal is a sine wave then that assumption is true, but if the signal has many frequencies the assumption may or may not be true.

4.5 The Function Generator

The oscilloscope, spectrum analyzer, and frequency counter are all instruments of analysis. We put a signal into them and we get out a measurement or display that gives us information about the signal. The *function generator* is the reverse. The function generator creates a signal; it creates the signal in electronic form. The user must specify the frequency and the amplitude by some means, perhaps by knobs on the front panel of the instrument, perhaps by computer control. The user can also specify the waveform, e.g., sine wave, sawtooth wave, square wave, or triangle wave. Such simple waveforms can be used to test audio and acoustical systems. They also are at the basis of electronically synthesized music, where they are called “oscillators.”

Digital function generators are sometimes called “waveform synthesizers.” A waveform synthesizer allows the user to generate complicated waveforms of any desired shape, even transient waveforms. Engineers at Ford in Dearborn, Michigan, use huge transducers under the wheels of test vehicles to subject these vehicles to realistic (and unrealistic) vibrations. The transducers are driven by waveform synthesizers that simulate bumpy roads, dips, potholes, etc.—anything that will torture a car and reveal weaknesses.

4.6 Virtual Instrumentation

Can a special-purpose instrument, such as an oscilloscope or a spectrum analyzer, be replaced by a general purpose computer? What features of the instrument would the computer need to accomplish this? It would need a way to acquire a signal (an input). It would need a way to process and represent the signal as selected by the user. It would need a way to display the result. The computer has these features. It has a sound card that can input signals. It has a memory and arithmetic capability that can follow a program. It has a monitor screen for display. Computer programs that emulate the functions of special-purpose instruments are generically known as virtual instruments. It is usual for the display to simulate the screen of the real special-purpose instrument. The display also depicts the knobs, pushbuttons, dials, and indicators that are typical of the real instrumentation. The user manipulates these controls with a mouse. Good virtual instrumentation can rival the quality and ease of use found in real instrumentation. An advantage of the real instrumentation is that real instrumentation is often used to measure signals that have been generated by a computer. The real instruments offer an independent confirmation.

Exercises

Exercise 1, The telephone

How many acoustical transducers are in a telephone handset? What are they?

Exercise 2, Fooling the frequency counter

On the graph in Fig. 4.8 draw a periodic signal that has two positive-going zero crossings per cycle. Explain why a frequency counter would display a frequency that is two times larger than the fundamental frequency of the signal. (A factor of two in frequency is called an “octave.”)

Exercise 3, All things come to him who waits.

A frequency counter displays a frequency as an integer number of cycles per second because it counts discrete events. For instance, it might display 262 Hz. Suppose you wanted better accuracy. Suppose you wanted to know that the frequency was really 262.3 Hz. What could you do?

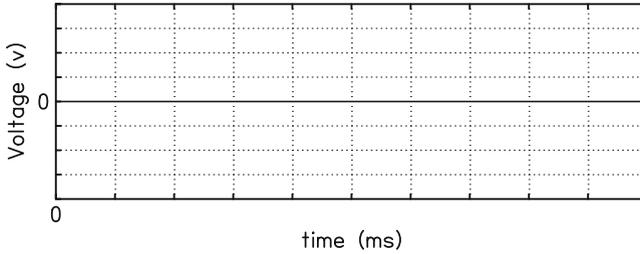


Fig. 4.8 Your signal to fool the counter with two positive-going zero crossings per cycle

Exercise 4, Make a list

Microphones and loudspeakers are transducers. Name some other transducers.

Exercise 5, Setting the sweep rate

Suppose you want to display two cycles of a 500-Hz sine tone on an oscilloscope. What should you choose for the period of the sawtooth sweep on the horizontal axis?

Exercise 6, The dual-trace oscilloscope

What is so important about a dual-trace oscilloscope? In what way does it have more than twice the capability of a single-trace 'scope?

Exercise 7, Oscilloscope deflection

Recall that like charges repel and opposite charges attract. The analog oscilloscope deflects the electron beam horizontally using charged plates on the right and left side of the CRT. If you want to deflect an electron (negative charge) to the left side of the oscilloscope screen, which plate would be positively charged, and which plate would be negatively charged?

Exercise 8, Reading the frequency from the oscilloscope

The oscilloscope has ten divisions in the horizontal direction. You observe that the sweep rate control is set to "0.5 ms/div." (Translation: 0.5 ms per horizontal division on the screen.) You see exactly four cycles of a sine tone on the screen. What is the frequency of the tone?

Exercise 9, Estimating the frequency

The oscilloscope is set up as in Exercise 8. You observe that a single cycle of the tone covers slightly more than 2 divisions. Estimate the frequency of the tone.

Exercise 10, Spectrum analyzer and oscilloscope

A signal is sent to both the spectrum analyzer and the oscilloscope. The spectrum analyzer display looks like Fig. 4.9. Explain why the oscilloscope tracing looks like Fig. 4.10.

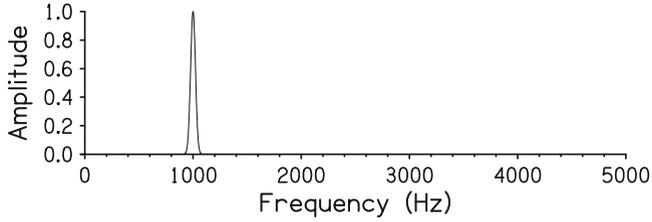


Fig. 4.9 Signal for Exercise 10 on the spectrum analyzer

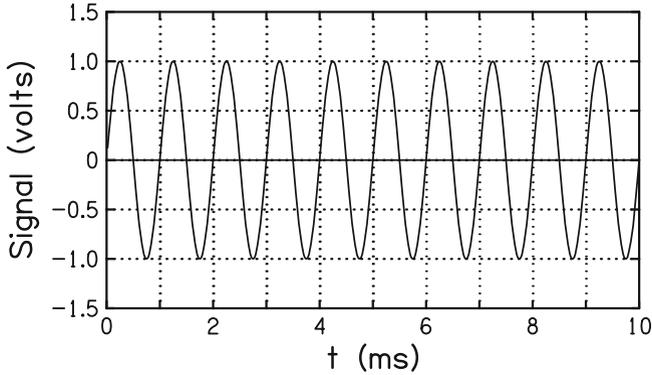


Fig. 4.10 Signal for Exercise 10 on the oscilloscope

Exercise 11, Oscilloscope grid

The oscilloscope grid in Fig. 4.10 has divisions spaced by 1 cm. How many volts per centimeter on the vertical scale? How many seconds per centimeter on the horizontal scale?

