EXPERIMENTER'S CORNER

By Forrest M. Mims

Experimenting with Piezoelectric Devices

Part 1. Microphones, Pushbuttons, and Ceramic Filters

WHEN certain crystals and ceramics are mechanically flexed, a voltage is produced. This phenomenon is known as the *piezoelectric effect*. The effect is reversible, too. This means that piezoelectric crystals and ceramics will contract or expand when a voltage is applied across them.

In this two-part column, we'll experiment with devices that exploit the electrical output of a mechanically flexed or stressed piezoelectric element. And we'll work with those that depend on the mechanical motion of an electrically excited piezoelectric element.

The Piezoelectric Microphone. The so-called *crystal* microphone is a piezoelectric acoustic transducer. Early crystal microphones used a Rochelle-salt crystal element. Today the piezoelectric element in many of these microphones is a polarized ceramic wafer about the size of a fingernail. The ceramic is easy to mass produce, and is stronger and more moisture resistant than Rochelle salt.

You can learn much about the operation of a piezoelectric microphone with the help of an oscilloscope. Connect the leads of the microphone directly to the scope's probe. Set the vertical sensitivity to about 0.1 V/div. Adjust the sweep speed to about 1 ms/div.

First, speak or whistle into the microphone. The scope's CRT will display a visual analog of the sound; and, depending upon the proximity of the microphone to your mouth, the amplitude will range from about 0.1 to 0.5 V. Since the waveform overlaps the no-signal centerline, it is ac in nature.

Next, rap the microphone with a pencil or thump it with a finger. If the microphone is an economy version, the scope's CRT will display a ringing pulse with an initial peak of perhaps 40 or 50 V. The duration of the initial pulse will be about 0.1 ms.

A better designed, highly damped, piezoelectric microphone will produce only a very low voltage when tapped or thumped. This is because its element is designed to prevent inadvertent high-voltage spikes that might damage the input stage of a preamplifier. This could happen if a microphone were dropped or otherwise given a strong blow.

You can perform a dramatic experiment to demonstrate the high-voltage output of a highly stressed piezolectric microphone element by connecting the leads from the microphone to a neon glow lamp as shown in Fig. 1. Select a very cheap or discarded microphone (perhaps one with a damaged foil diaphragm), since it is necessary to remove the microphone's cover.

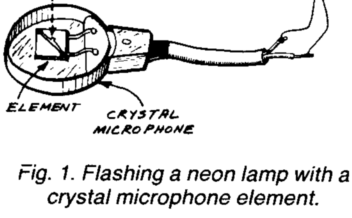

Fig. 1. Flashing a neon lamp with a crystal microphone element.

Tap the center of the foil diaphragm with a pencil or thump it with a finger, and the lamp should flash. The voltage pulse will be up to a millisecond wide and its amplitude may reach a few hundred volts!

It's not necessary to remove the diaphragm to conduct this experiment. However, if you wish to remove the foil, peel it from around the edge of the microphone case first. Then *carefully* pull it away from the central metal support that is attached to the piezoelectric element. Small scissors may help.

If you remove the foil, do not directly strike the element to light the neon lamp. Instead, strike the metal support bar that bridges two opposite corners of the element and provides a mounting point for the diaphragm. Be careful! The sole support for the piezoelectric element is probably a pair of rubber vibration-damping bumpers on two opposite corners of the element. The element is easily detached from these supports. Also, the two leads emerging from one side of the element are very fragile.

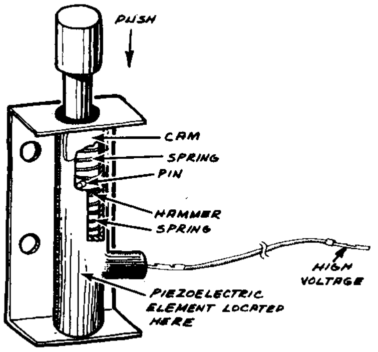

Fig. 2. Vernitron 3652 piezoelectric high-voltage pushbutton.

The Piezoelectric Pushbutton. Piezoelectric pushbuttons are used to ignite the fuel of some cigarette lighters, laboratory burners, and home furnaces. They produce a brief spike of up to 18,000 V and can make an arc up to $^{3}/_{16}$ in. in length.

For several years I've enjoyed experimenting with a Model 3652 high-voltage pushbutton made by Vernitron Corporation (Piezoelectric Division, 232 Forbes Road, Bedford, OH 44146). A similar device made by Vernitron is used as a solid-state igniter for outdoor cooking grills. The company has also manufactured hundreds of thousands of 0.1-inch, piezoelectric, ceramic cubes used to power the flash in compact cameras.

A pictorial view of the 3652 high-voltage pushbutton is shown in Fig. 2. The piezoelectric element is a compact slug about $^{5}/_{8}$ by $^{3}/_{16}$ in. Most of the unit's size is taken by the spring-loaded trip hammer that strikes the piezoelectric element.

To operate the unit, the pushbutton is pressed downward with a force of a few pounds. This compresses the upper spring and moves the cam toward the pin on the trip hammer. When

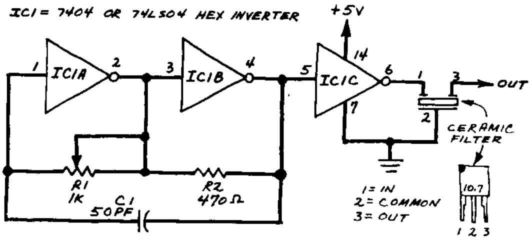

Fig. 3. Test circuit for a ceramic filter.

the cam pushes the pin into the drive slot, the hammer is triggered and slammed with a good deal of force against the piezoelectric element. When the pushbutton is released, the lower spring, which was compressed by the downward motion of the hammer, returns the hammer to its resting position where it is again ready to be driven against the piezoelectric element.

The arc produced by the piezoelectric pushbutton can be viewed by placing the output electrode near the unit's metal frame. For best results, the arc should be viewed in subdued light or against a dark background. Unless you want to feel a potent tingle, keep you fingers away from the output electrode when the button is pressed!

An interesting experiment is to connect a piezoelectric pushbutton to a long xenon flash tube. When the button is pressed, a thin violet arc will immediately appear between the tube's electrodes.

With suitable rectification it should be possible to use a piezoelectric pushbutton to charge a capacitor to a very high voltage. Of course the capacitor would have to be rated for the expected voltage. This might make possible a very simple power supply for Geiger counters and infrared image-converter tubes.

An 18,000-V piezoelectric pushbutton is available for $9.95 plus $2.45 for packing and guaranteed delivery from Edmund Scientific (101 E. Gloucester Pike, Barrington, NJ 08007). Specify catalog number 42,102 when ordering.

The Ceramic Filter. The ceramic filter, a most unusual piezoelectric device, is dependent upon the mechanical resonance of a piezoelectric ceramic wafer. When a signal is applied to its input, a surface wave is induced in the ceramic. If the frequency of the wave matches the resonant frequency of the ceramic, the wave will travel along the surface of the ceramic where it induces a piezoelectric voltage at a second pair of electrodes. Otherwise no signal is passed through the filter. In effect, then, the ceramic filter functions like a frequency-selective, isolation transformer.

Ceramic filters are widely used as 455-kHz intermediate-range filters in AM radio receivers. They are also used as 10.7-MHz filters in FM receivers and television sets. At these frequencies, the size of the filter is much smaller than an equivalent electronic filter. For example, a typical 455-kHz ceramic filter is a disc 0.2 in. across and from 0.1 to 0.4 in. thick. If the signal applied to a center electrode and a common electrode on the back side of the disc is at or very near 455 kHz, then the disk will vibrate and induce an electrical signal at a third electrode around the upper edge of the disk.

Figure 3 is a circuit that demonstrates the operation of a 10.7-

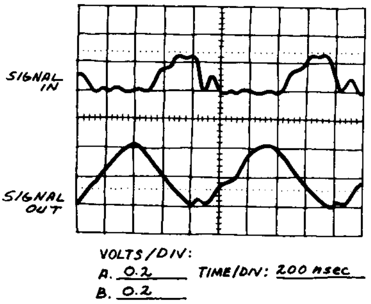

Fig. 4. A 10.7-MHz signal in a ceramic filter.

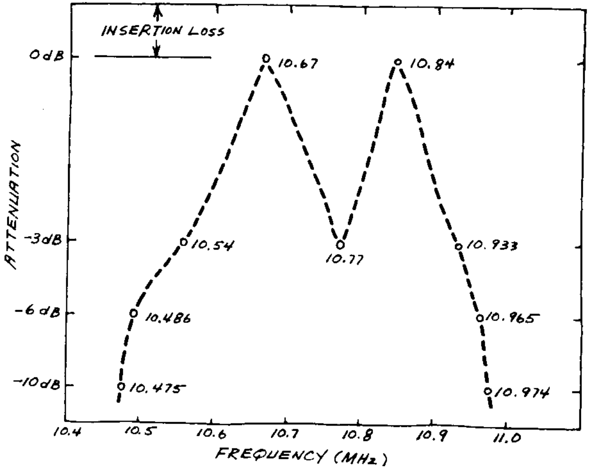

Fig. 5. Measured bandpass of a 10.7-MHz ceramic filter.

MHz ceramic filter such as the SFE 10.7MA5-A made by muRata Corporation of America (1148 Franklin Road, S.E., Marietta, GA 30067) and available for about one dollar from Radio Shack.

In operation, two inverters in a 7404 or 74LS04 hex inverter form a high-frequency oscillator whose output signal is buffered by a third inverter and fed into a ceramic filter. The frequency of the oscillator, which is determined by *R1*, can be adjusted from about 9 to 19 MHz with the component values shown. Much lower frequencies can be produced by increasing the value of *C1*.

Figure 4 shows the signal from the oscillator before and after its passage through the filter, with *R1* adjusted to provide the filter's peak frequency response. Note that the output signal appears to have about twice the amplitude of the input signal. Actually, the output signal is an ac version of the single-polarity input signal, hence the apparent doubling of its amplitude.

Also note that the output signal is phase delayed and is a much smoother, cleaner version of the input signal. The input signal might be cleaned up somewhat by optimizing component placement and using direct, point-to-point wiring instead of a solderless breadboard. Why is the output better shaped than the input? The acoustic wave that travels across the surface of the ceramic dampens imperfections in the input signal.

How effective is a ceramic filter? Figure 5 is a frequency-response plot made with the help of the circuit in Fig. 3 and an oscillocope. Note that the filter has a double peak with almost a − 3-dB valley or ripple at the specified peak response region. Of more significance is the rapid decrease in response beyond the − 6-dB points. The − 3-dB bandwidth is about 390 kHz. At − 10 dB the acceptance window is about 500 kHz.

My measurements do not agree as closely as I would have liked or expected with those given in muRata's published specifications for the SFE 10.7MA5-A. The − 3-dB bandwidth, for example, is given as 280 ± 50 kHz. Though the ripple for this filter is not given, a graph published in muRata's literature suggests a ripple considerably less pronounced than the − 3 dB I measured.

A 10.7-MHz Ceramic Oscillator. Quartz crystals are normally used to regulate precision oscillators. I've found that a ceramic filter will also work, but without nearly the precision quartz provides.

Figure 6 shows a 10.7-MHz ceramic oscillator. The circuit is virtually identical to the one in Fig. 3. The only exception is that *C1* in Fig. 3 has been replaced by the ceramic filter.

The variety of frequencies available with ceramic filters is much less than the vast number of quartz-crystal frequencies. Nevertheless, the circuits in Figs. 3 and 6 suggest an interesting application: a matched radio-frequency oscillator and frequency-sensitive detector. The signal from the transmitter can be coupled directly or through the air via a fast-rise-time LED or by radio waves. (Additional circuitry will be required to implement this application.) Note that you will have to observe FCC regulations that apply to radio-frequency emissions. If you use a line-powered supply to operate the circuit, a nearby TV set may be subjected to severe video interference.

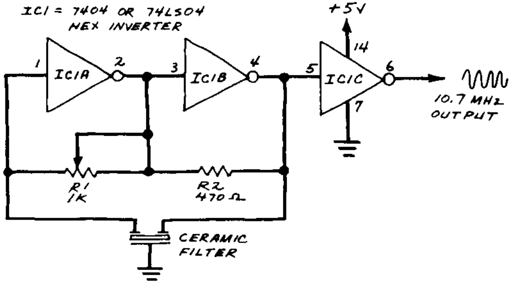

Fig. 6. Schematic diagram of a 10.7-MHz ceramic oscillator.

The chief advantage of this application is the very low cost and compact size of the ceramic filter used in both the oscillator and receiver. The ceramic filter used to produce the plot in Fig. 5 oscillated at 10.71950 MHz when *R1* was 500 ohms. A second filter gave a frequency of 10.72105 MHz. This relatively minor difference is of little consequence since the oscillator can be tuned a few tens of kilohertz in either direction by changing the setting of *R1*. ◇

By Forrest M. Mims

Experimenting with Piezoelectric Devices

Part 2. Piezo-Alerters and Crystal Oscillators

WE experimented with piezoelectric spark generators, microphones, and filters in Part 1 of this two-part series on piezoelectric devices. This month, we'll discuss using piezoelectric alerters and quartz-crystal oscillators.

Piezoelectric Alerters. Crystal microphones and speakers are designed to operate across a wide band of audio frequencies. Piezoelectric alerters, however, are generally designed to operate at a fixed or relatively narrow audio-frequency band. They are true solid-state sound sources.

As far as I know, the first commercial piezo-alerter was the Mallory Sonalert®. Sonalerts are available in various kinds of housings having a range of audio outputs. Most include self-contained drive circuitry.

I first purchased a Sonalert in 1966 and a few years later used it to measure the velocity of a model rocket in flight. The Sonalert, a Model SC628 emitting a tone of 2.9 kHz, was installed in the base of a model rocket. The rocket's engines were installed in pods attached to its center tube. The sound from the Sonalert was tape recorded from the ground during the rocket's flight. By measuring the doppler shift, it was possible to determine the rocket's velocity.

Alerter Construction and Operation. Thanks to their miniature size, low current consumption, and penetrating sound, piezoelectric alerters are commonly used in digital watches, clocks, smoke alarms, pagers, appliances, calculators and games. A typical alerter is a metal disc from 25 to 40 mm in diameter upon which is bonded a smaller disc of piezoceramic material. A conductive film is deposited over the ceramic layer, and electrodes are attached to it and the metal disc.

Often alerter discs include a *feedback electrode* made by isolating a small section of the metal film on the back of the piezoceramic material. The feedback electrode, which is shown in Fig. 1, simplifies the design of driver circuits and stabilizes the alerter's oscillation frequency. Piezo-alerter discs can be purchased alone or installed in plastic holders complete with connection leads. Versions with self-contained driver circuits much like the Mallory Sonalert are now available from several companies.

It is essential to properly mount an alerter disk for maximum sound output. If the vibrating portion of the disk is cemented or otherwise attached to a mount, severe attenuation of the device's sound output will occur.

Figure 2 shows three acceptable ways to mount an alerter disc. The *center mount* permits the outer rim of the disc to vibrate, while the *edge mount* permits the entire disc to vibrate. Both of these methods permit the disc to vibrate across a range of audio frequencies.

The *nodal mount*, also shown in Fig. 2, is best for a very-loud, single-frequency tone. The node of a piezo-alerter disc is a concentric ring around the center of the disc at which vibration at a fixed frequency is at a minimum (or even non-existent). Ideally, the diameter of the nodal ring is 0.55 times the diameter of the metal disc. The actual diameter, however, varies from the predicted value due to the presence of the piezoceramic disc and nonuniformities in the metal disc.

One way to find the actual location of the nodal ring is to sprinkle fine sand or powder on a piezo-alerter disc being driven at a desired frequency by a suitable oscillator. The powder particles will gradually bounce into the nodal region and form a thin, circular ring around the center of the disc.

Piezo-Alerter Driver Circuits. A piezo-alerter can be driven directly by a variable-frequency signal generator. Even alerters having nodal-mounted discs can be operated across the audio spectrum, although edge- and center-mounted discs work best across a wide band of audio frequencies.

Figure 3 shows a simple, single-transistor driver for a piezo-alerter having a feedback terminal such as the model PKM11-6A0 from muRata Corporation of America (1148 Franklin Rd., SE, Mariette, GA 30067). This alerter is also available from Radio Shack (catalog number 273-064).

The PKM11-6A0 can be operated over a specified range of 3 to 15 V (mine works down to 1 V) and has a current consumption over this range of 2 to 12 mA. Its output sound-pressure level ranges from more than 80 dB at 3 V to more than 90 dB at 15 V. Its resonant frequency is within 700 Hz of 6.5 kHz. It has an operating temperature range of − 20° to + 60° C and weighs only 1.5 grams.

A test version of the circuit in Fig. 3 drove the alerter at a frequency of 6772 Hz when V_{CC} was 3 V. This frequency is controlled by the dimensions of the feedback tab on the alerter disc and not the components of the oscillator. For example, changing *R1* over a range of 100 to 330 kilohms altered the shape of the waveform but not the frequency. The frequency is nearly independent of changes in V_{CC}.

Figure 4 shows a simple, single-chip, CMOS oscillator suitable for driving a piezo-alerter. This circuit is adapted from one in a Gulton Industries application note. Notice how the 4049

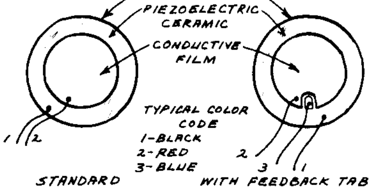

Fig. 1. Piezoelectric alerter elements.

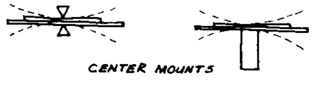

Fig. 2. Three mounting arrangements for piezoelectric alerter elements.

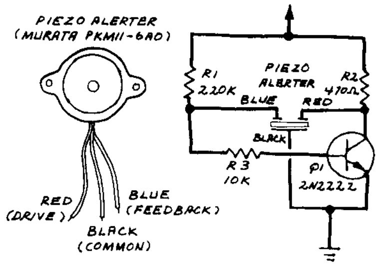

Fig. 3. Piezoelectric alerter driver circuit.

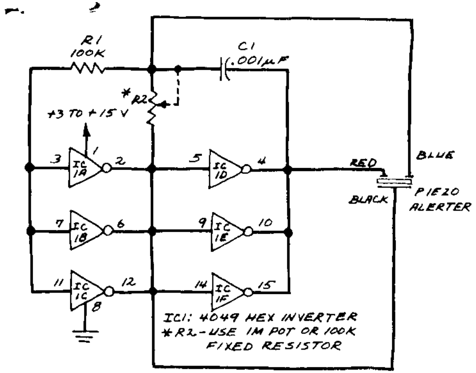

Fig. 4. An IC alerter driver circuit.

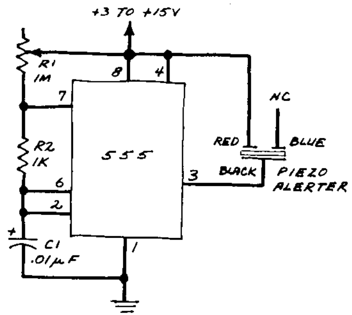

Fig. 5. Adjustable-frequency driver circuit.

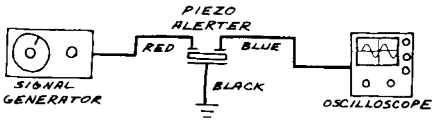

Fig. 6. Using a piezoelectric alerter as a signal filter.

gates are connected in parallel to permit higher drive current.

The circuit in Fig. 4 has the advantage of having an adjustable frequency. A breadboard version I built operated over a range of about 185 Hz to 7 kHz. The frequency change, however, was not gradual but occurred in steps. When the piezo-alerter reached its resonant frequency of around 7 kHz, changing *R2*'s resistance had no effect.

The circuit in Fig. 5 will drive piezo-alerters with and without feedback terminals at a variable frequency. Unlike the circuit in Fig. 4, this circuit provides a gradual, nonstepped output tone. A slow *pock . . . pock . . . pock* sequence can be produced by using a 0.47-μF capacitor for *C1*.

The operation of a piezo-alerter's feedback electrode can be graphically demonstrated by connecting the anode of a red LED to the blue lead of the alerter in Fig. 5. Connect the LED's cathode to ground. The output from the blue lead easily exceeds a few volts, more than enough to forward-bias the LED and cause it to emit a dim glow.

Keep in mind that there is no electrical connection between the feedback electrode and the main electrode on the piezoelectric ceramic disk. The voltage at the feedback terminal is true piezoelectricity. It is generated in response to the pressure wave that appears in the piezoelectric ceramic disk. (The pressure wave is generated in response to the drive signal.) The LED demonstration shows how a piezoelectric device can function as a solid-state transformer or isolator.

Using an Alerter as a Filter. Figure 6 shows how to demonstrate the use of a piezo-alerter as a ceramic filter. The model PKM11-6A0 exhibited frequency-response peaks at 2.3 kHz, 7.0 kHz, 18 kHz, 27 kHz and 45 kHz. While a scope is helpful, it's possible to monitor the filter's operation by simply listening to the change in amplitude of the filter's sound output as the signal generator's frequency is varied. Of course this method only works at audio frequencies.

Incidentally, I attempted to measure the delay introduced by the piezoelectric ceramic with the help of a dual-trace 100-MHz oscilloscope. The speed of sound in the ceramic is around 5000 m/s according to *Reference Data for Radio Engineers* (ITT, Howard W. Sams & Co., 1975, p. 4-44). Since the gap between the main and feedback electrodes on the piezo-alerter disc is 0.5 mm, the expected delay is 100 nanoseconds.

Though the driver circuit for the test, the 555 oscillator in Fig. 5, provided clean leading- and trailing-pulse edges, the signal elicited from the feedback terminal had too much ringing for an accurate measurement of the delay. While I *think* I monitored a 100-ns delay, I cannot be certain due to the sloppy appearance of the feedback pulse. Perhaps you will have better results.

Other Alerter Ideas. The very narrow audio spectrum produced by piezo-alerters makes them ideal for use in experiments with sound. With the help of a microphone and an oscilloscope, you can easily demonstrate constructive and destructive interference of sound waves. Try pointing the microphone at the alerter while moving the microphone back and fourth. Or point both the alerter and the microphone at a flat metal or plastic panel which you can move back and forth. The proper arrangement will reveal a periodic amplitude fluctuation in the received signal, which you can view on the scope.

Note that, in an enclosed room, the sound of an alerter can vary dramatically in intensity. This is a result of the way the single-frequency acoustical waves from the alerter form complex interference patterns. Negative interference causes the formation of *dead spots* where the sound is virtually imperceptible. Constructive interference forms regions where the sound is uncomfortably shrill.

Sounds from radios, televisions, phonographs and people span a wide range of audio frequencies. Therefore, the effects of interference are not nearly as noticeable.

The effects of the acoustical interference caused by the pure tone emitted by an alerter may or may not be desirable. It is certainly attention getting to walk by an alerter and notice the changes in sound intensity. But it can also be confusing, particularly if you are trying to find the source of the sound in an enclosed room having many flat, hard reflecting surfaces! The resultant interference problems can be avoided by using multiple or swept tone alerters.

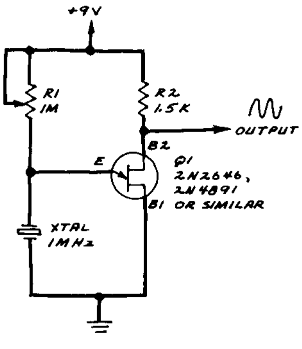

Fig. 7. UJT oscillator.

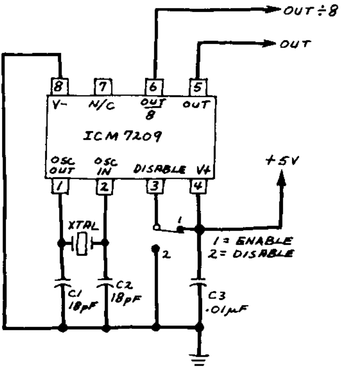

Fig. 8. Clock-pulse generator.

If you enjoy experimenting, try using a piezo-alerter as a microphone. You'll find that alerters with nodal mounting function as *frequency selective* sound detectors. Also, try adding a tube or reflector to an alerter to form a directional sound source. You can try operation at resonant ultrasonic frequencies. You can even develop various kinds of sonic radar circuits or try operating an alerter under water.

Alerter Precautions. Data sheets for piezo-alerters note that mechanical shock can cause them to generate high-voltage spikes that can damage their drive circuit and perhaps other associated circuits. This problem can be alleviated by installing an appropriately rated protection diode directly across the alerter.

Another precaution concerns the placement of an alerter on a circuit board. Be sure to mount the alerter on a rigid, fixed portion of the board. If the alerter is mounted on a cantilevered portion of a circuit board, it may set up vibrations in the board, substantially reducing its sound output.

Finally, a precaution I've *not* seen in the data sheets concerns the shrill sound which can be produced by some alerters. I've found that the sound can easily produce a piercing headache. While experimenting with the circuits described above, I eventually resorted to covering the aperture of the alerter with clay or tape to muffle the sound output.

Quartz-Crystal Oscillators. The final piezoelectric device we will consider is the quartz-crystal oscillator. Precision-cut wafers of quartz are used to make piezoelectric resonators having exceptional frequency stability. Figure 7 shows an ultra-simple, crystal-controlled, unijunction-transistor oscillator that uses only four components. The quartz crystal replaces a capacitor normally used in this circuit. The oscillation frequency can be tuned from about 50 kHz to exactly 1 MHz when the crystal has a resonant frequency of 1 MHz. Tuning is accomplished by altering the resistance of *R1*.

If you monitor the output of the oscillator in Fig. 7 with an oscilloscope, you will notice that the oscillation frequency tends to change in jumps as *R1* is adjusted. This is a result of the crystal's oscillating at various harmonics of its 1-MHz resonant frequency. Near 1 MHz, the oscillator quickly locks onto the crystal's resonant frequency.

The circuit in Fig. 7 is useful for understanding the operation of a simple quartz-crystal-controlled oscillator. It can also be used to supply a marker frequency to calibrate oscilloscopes, signal generators, and shortwave receivers.

Figure 8 shows a very useful crystal-controlled, clock-pulse generator. The circuit is designed around Intersil's ICM7209, a CMOS general-purpose timer chip. The crystal can be any quartz crystal having a resonant frequency of 10 kHz to 10 MHz. The circuit consumes only about 11 mA when powered by a 5-V supply and requires only four external components.◇

ELECTRONICS NOTEBOOK

Experimenting With the Piezoelectric Effect

By Forrest M. Mims III

Piezoelectric material has the ability to transform mechanical movement into a voltage. The effect works both ways, for a piezoelectric material will generate a voltage when it is bent, stretched or compressed. This is the first of two in-depth columns that will deal with piezoelectricity. In this installment, I'll cover applications for piezoelectricity and various kinds of piezoelectric materials, following which we'll experiment with a piezoelectric fan and some high-voltage piezoelectric generators.

Applications

Piezoelectric devices have become one of the most important and diversified classes of electronic components. If this claim seems to be somewhat exaggerated in this age of silicon microchips, just look around you. Chances are, your life is very much influenced by piezoelectricity.

You're probably very much aware of most or all the applications for piezoelectronics I am about to list. But you may never have seen so many of these applications described in one space.

Let's start with the watch on your wrist. If it is battery powered and digital, its time base is a piezoelectric quartz crystal that oscillates at a frequency of 32,768 Hz (2^{15} Hz). If your watch has an alarm function, the sound you hear from it at the preset time is almost certainly generated by a piezoelectric ceramic wafer. Similar sound generators are installed in microwave ovens, alarm clocks, fever thermometers, telephones, paging receivers and computers. They are also frequently used in electronics-assisted photographic and all-electronic video cameras, timers and fire/smoke and intruder alarms.

Speaking of smoke alarms, piezoelectric trip hammers provide ignition sparks for gas heaters, cigarette lighters, outdoor gas-type cooking grills and gas lanterns. Some gasoline engines incorporate a piezoelectric element in place of an ignition coil. The element produces a spark each time it is struck by a rotating cam.

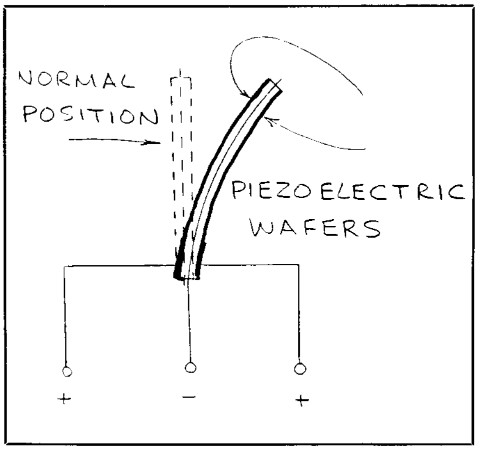

Fig. 1. Piezoelectric bimorph bender.

The color in your TV receiver is regulated by a quartz crystal that oscillates at a frequency of 3,579,545 Hz (commonly abbreviated to 3.58 MHz). Other piezoelectric devices filter the signal in your FM radio, faithfully transform the high-frequency audio signals from your receiver into sound, control the frequency of your CB rig and generate the timing signals in your personal computer. Other applications of piezoelectric devices include microphone elements, motors, switches and many kinds of sensors that are capable of detecting heat, sound, liquid levels and pressures.

Piezoelectric crystals provide accurate timing for household appliances like clothes dryers and microwave ovens. Piezoelectric wafers vibrating at ultrasonic frequencies permit boaters and fishermen to accurately monitor bottom conditions and find fish. Thanks to a related technology, several years ago, my wife and I were able to view our third child four months before she was born.

The ultrasonic waves produced by wafers of piezoelectric ceramic can be so intense that they can violently agitate a fluid in which they are immersed. It is this principle that makes possible ultrasonic humidifiers and jewelry cleaners. The ultrasonic waves produced in this fashion can be exceptionally energetic. Indeed, a piece of wood can be ignited by pressing it against a ceramic plate that is intensely vibrating at ultrasonic frequencies.

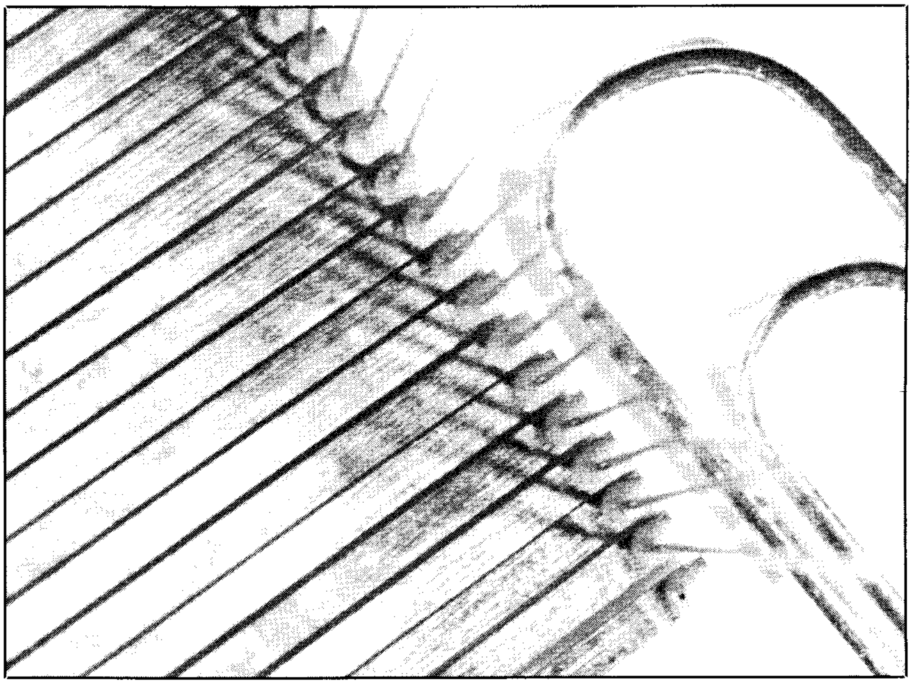

Fig. 2. Bimorphs used as a tactile stimulator in a reading machine for the blind.

These are only some of the most common examples of piezoelectricity applications. There are literally hundreds of applications for the dozens of different kinds of piezoelectric devices that are now available.

Early Uses of the Piezoelectric Effect

All the applications for piezoelectronics listed above can be traced to a discovery made by Pierre and Paul-Jacques Curie more than a century ago. In 1880, the two brothers discovered that many different crystals produce a voltage spike when a weight was placed on them. The next year, they discovered that applying a voltage to a crystal caused the crystal to lengthen. They named these phenomena the "piezoelectric effect" after the Greek word "piezien," which means to press.

The first major use of the piezoelectric effect was in detection of submarines during World War I. It was later discovered that piezoelectric quartz crystals can be used to precisely regulate the frequency of radio transmitters. Tens of millions of quartz crystals were produced by the United States for use in military radios during World War II.

Quartz remains the most important piezoelectric crystal. Quartz crystals, of course, are still widely used to keep both radio transmitters and radio receivers properly tuned. An important advantage of quartz is that it is relatively insensitive to changes in temperature. This is why you can take a hand-held transceiver out on a frigid night and maintain contact with a base station that is kept warm by a space heater.

Another important early application of quartz crystals that is still in widespread use is the filtering of electronic signals. In this application, quartz crystal filters are especially useful in various kinds of cable and radio communication system links.

Development of these and other early applications for piezoelectricity eventually led to the hundreds of piezoelectronic devices now in widespread use. Later, we'll experiment with a piezoelectric fan.

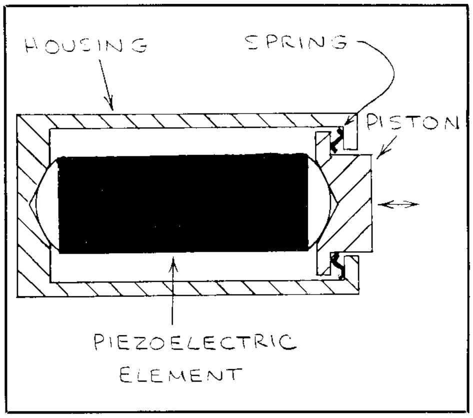

Fig. 3. Burleigh Instruments, Inc., piezoelectric pusher actuator.

First, however, let's examine some piezoelectric materials.

Many different naturally occurring and man-made crystals exhibit the piezoelectric effect. I've already noted that quartz is among the most efficient and important of piezoelectric materials. Quartz crystals are physically sturdy and, unlike some other piezoelectric materials, does not absorb water. These crystals are also relatively immune to changes in temperature. For applications in which even their limited response to temperature changes is unacceptable, quartz crystals can be warmed to a constant temperature by a miniature heater known as a "crystal oven."

The lack of a center of symmetry is what gives quartz and other crystals their piezoelectric properties. Rochelle salt crystals, which have no center of symmetry, are efficient piezoelectric materials that have been widely used in many applications, including phonograph pickups, microphones and earphones. Unfortunately, Rochelle salt crystals are fragile and sensitive to temperature changes. Other piezoelectric crystals include tourmaline, lithium niobate, lithium sulphate and ammonium dihydrogen phosphate.

After quartz, the most important piezoelectric materials are ceramics like barium titanate, zirconate titanate and lead zirconate-lead titanate. Ordinarily, these polycrystalline materials have no piezoelectric properties. During the manufacturing process, a strong electrical field aligns the crystallites within the material, thereby giving the material piezoelectric properties. This process is called "poling." Piezoelectric ceramics have many applications and are relatively inexpensive.

Certain plastics can also be given piezoelectric properties during their manufacture. Among the most important are polytrifluourethylene, polyvinyl chloride and polyvinylidene fluoride. The last polymer has by far the best piezoelectric properties. Like piezoelectric ceramics, piezoelectric plastic films have many practical applications. Moreover, they are inexpensive and flexible and can easily be cut to any desired shape.

Piezoelectric Bimorphs

Mechanical movement of a thin plate or sheet of piezoelectric material in response to an applied voltage can be greatly increased by bonding it to a second plate or sheet. The resulting sandwich-like structure is known as a "bimorph."

Shown in Fig. 1 is a bimorph connected to a voltage source. When one end of the bimorph is held in a fixed position, the opposite end will bend away from its normal position when a voltage is applied. When the polarity of the applied voltage is reversed, the bimorph will bend in the opposite direction. The bimorph will also generate voltage when it is bent, with the polarity of the voltage depending on the direction of bend motion.

Bimorphs can be made from sandwiches of ceramic or plastic piezoelectric materials. Their many applications include stereo phonograph pickup cartridges, microphone elements, earphone elements and vibration sensors. Figure 2 shows an array of ceramic bimorphs that provide a tactile output for a reading machine for the blind. Vibration of the wires attached to the ends of each bimorph can be detected easily by a finger tip.

Bimorphs are mounted in either of two ways. End-supported bimorphs are provided with mounting supports at both ends. The center of the bimorph then becomes its flexible region. Cantilevered bimorphs are mounted at only one end such

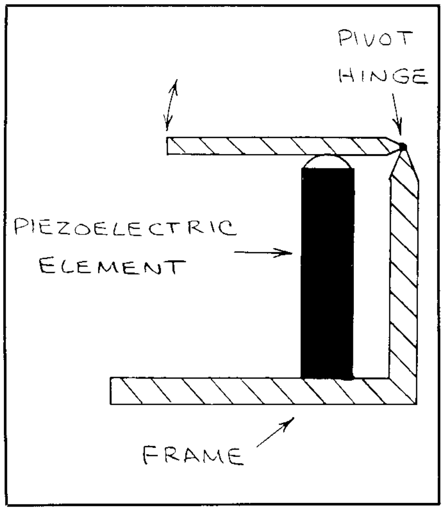

Fig. 4. Burleigh Instruments piezoelectric levered actuator.

that their free end becomes the flexible region.

Bimorphs are manufactured by several companies, including Vernitron Piezoelectric Division (232 Forbes Rd., Bedford, OH 44146-5478). I recently experimented with some bimorphs made by this company. When driven by an audio-frequency signal, a bimorph will produce an audible "buzz" or tone. The sound can be greatly amplified by taping the bimorph to an index card. At low drive frequencies, the vibration of the bimorphs I experimented with was very easily felt by a fingertip.

Piezoelectric Actuators

Piezoelectric actuators are specifically designed to produce movement in response to a control voltage. Many different kinds of actuators are available. They can be made from bimorphs or stacks of piezoelectric disks.

Piezoelectric micropositioners are actuators that move various electronic and optical devices over very short distances. One common application for micropositioners is the precise movement of optical detectors and emitters through the focal region of a lens. Micropositioners are also used to precisely align optical fibers and microminiature optical components.

Operation of a common type of micropositioner relies on the fact that a properly poled ceramic disk will expand in thickness when a voltage is applied across it. Since a single disk might expand only a fraction of a micrometer, practical micropositioners are made by stacking many disks into a cylinder. Total available expansion of the length of the cylinder is the sum of the expansion of the individual disks from which it is formed. One such cylinder made by Burleigh Instruments, Inc. (Burleigh Park, Fishers, NY 14453) gives an expansion of about 5 micrometers per 100 applied volts.

Figure 4 shows a lever arrangement that provides more movement using the same kind of piezoelectric element. However, the movable arm greatly amplifies the element's movement. According to information supplied by Burleigh Instruments, the movement equals the extension of the element times the ratio of the length of the lever arm to the distance between the end of the element and the pivot hinge.

"Worm Motors"

In recent years, various kinds of piezoelectric motors have been developed. Some are in commercial use. For example, some camcorders incorporate piezoelectric lens focusing motors.

The operation of one kind of piezoelectric motor resembles the motion of an inch worm. One such motor is appropriately names the Inchworm Motor™ and is made by Burleigh Instruments. It consists of three piezoelectric cylinders through which a movable shaft is passed. By applying a pattern of control voltages to each cylinder, the shaft can be made to move in either direction.

Shown in Fig. 5 is a diagram that illustrates how the motor is made and how it works. The two outermost piezoelectric cylinders squeeze against the shaft when they are actuated by an applied voltage. The center cylinder extends when it is actuated. Here is what occurs:

Initially, no voltage is applied. Outermost cylinders 1 and 3 are fully expanded and center cylinder 2 is not extended. A voltage is then applied to cylinder 1 to hold the shaft in place. Next, a voltage is applied to cylinder 2 to extend the motor along the shaft. The voltage is then removed from cylinder 1 to unclamp the left end of the shaft. Then the voltage on cylinder 2 is removed to permit the cylinder to contract. Cylinder 1 is then clamped to hold the shaft in place and cylinder 3 is unclamped.

This sequence is repeated to move the shaft through the motor from right to left. A Burleigh Inchworm Motor gives a shaft movement of greater than 2 millimeters per second when the frequency of the clamping pulses is 800 Hz.

Piezoelectric Fans

The "motor" for a piezoelectric fan is a ceramic or plastic bimorph bender that is driven by a sinusoidal voltage source. The fan doesn't have a rotating blade or blower as does a conventional fan. Ceramic fans move air by means of a vibrating sheet of Mylar that is bonded to one end of the bender. The entire length of a plastic bender vibrates. The result in ei-

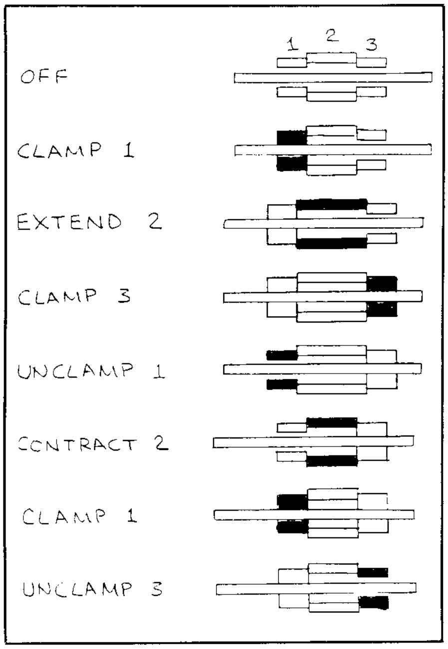

Fig. 5. Burleigh Instruments piezoelectric Inchworm Motor.

ther case is a device you have to see to believe.

Let's first consider the case of the bimorph bender. When a sinusoidal voltage is applied to the bimorph bender, one end of which is clamped in a fixed position, the free end of the bender vibrates. If the sinusoidal voltage has an audio frequency, you can hear the sound produced by the vibrating bender. While movement of the end of the bender is almost imperceptible to the human eye, you can easily feel the vibration by touching the end of the bender.

The length of the bender and any extension vane attached to it determines the resonant frequency of the assembly. When the frequency of the voltage applied to the bender matches the resonant frequency of bender and vane, the vane flaps rapidly back and forth. This motion, which resembles the movement of the tail of a fish, generates a turbulent vortex of air along and toward the end of the trailing side of the vane. When the vane reaches the end of its movement and begins to move in the opposite direction, the vortex of air flies off the end of the vane. The rapid back-and-forth motion of the vane creates a series of vortexes that merge into a stream of air.

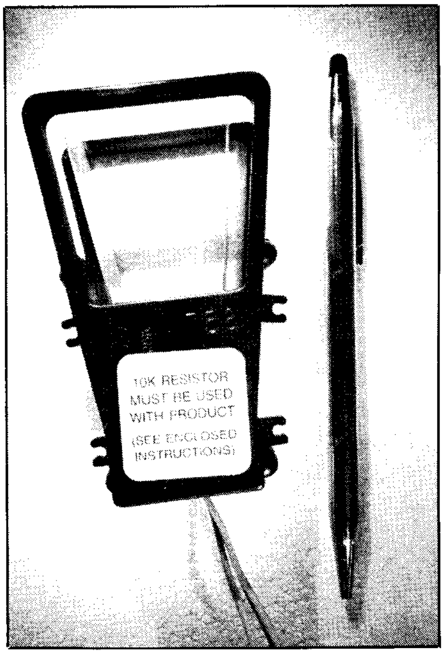

Fig. 6. A fan manufactured by Piezo Electric Products, Inc.

While a single vane will move air, a much better approach is to use two closely spaced vanes. This doubles air movement and merges it into a reasonably directional stream.

Thus far, we have described ceramic benders with an extension vane. This discussion also applies to plastic benders. The only difference is that a plastic bimorph bender requires no extension vane. Unlike ceramic bimorph benders, plastic benders are flexible enough to flap back and forth on their own.

Experimenting With a Piezoelectric Fan

Piezo Electric Products, Inc. (212 Durham Ave., Metuchen, NJ 08840) manufactures dual-vane piezoelectric fans. Shown in the photo in Fig. 6 is one of the company's fans. You can purchase individual Quadrature Fan Module B piezoelectric fans like the one shown from Edmund Scientific Co. (101 E. Gloucester Pike, Barrington, NJ 08007) for $16.95 plus postage by ordering Cat. No. D36,563.

A graph that profiles the airflow from a Module B fan is shown in Fig. 7. The relatively directional nature of the air flow makes this fan well suited for cooling individual components in a circuit, such as power transistors and transformers.

I've experimented with a Module B piezoelectric fan purchased from Edmund Scientific. This fan is designed to be powered directly by 117-volt, 60-Hz line current through a 33,000-ohm current-limiting series resistor. The fan moves 7 cubic feet of air per minute, and it consumes only about 10 percent of the power required by a conventional electromagnetic fan that moves the same amount of air. It starts instantly, requires no lubrication, produces no electrical noise, and is considerably quieter than a conventional fan.

The Module B piezoelectric fan has no bushings, bearings or other parts that wear out. Therefore, its life expectancy is very long. The manufacturer claims to have operated identical fans for more than four years continuously without failure; so reliability is also very high.

A piezoelectric fan appears to be more fragile than an electromagnetic fan. Indeed, the instructions packed with the fan I purchased included the following caution notice:

"The gray ceramic driver for the blade is very delicate and easily broken. Exercise care in unpacking and handling. Handle fan motors without housing by the black mounting block *only*."

Though the driver elements are considered fragile, Piezo Electric Products claims the fan will survive a 4-foot drop to a concrete floor. While I haven't performed a drop test to verify this claim, I've physically restrained one or both of the vanes while they were in motion and intentionally allowed the moving vanes to strike many different objects. I've also driven the fan across a wide range of frequencies and with both sine waves (as recommended by the manufacturer) and square waves (which are definitely not recommended by the manufacturer). Even after all this abuse, my tortured little fan continues to gently buzz along even as these words are being typed.

Though Piezo Electric Products' piezoelectric fan is specified for operation at 117 volts (don't forget the series resistor!), the fan will operate at lower voltages with reduced air movement. This means you can power it with a simple battery-powered transistor or IC oscillator circuit and step-up transformer arrangement. The most important requirement is that the supply voltage be a 60-Hz sinusoidal wave. Other frequencies can be applied to the fan, but the vanes are designed to be mechanically resonant at 60 Hz and will not respond to other frequencies.

As I already mentioned, you have to see a piezoelectric fan in operation to fully appreciate the fact that it actually works. The second best way to demonstrate that these fans really work is to photograph the vanes of the same fan with the power switched off and then on.

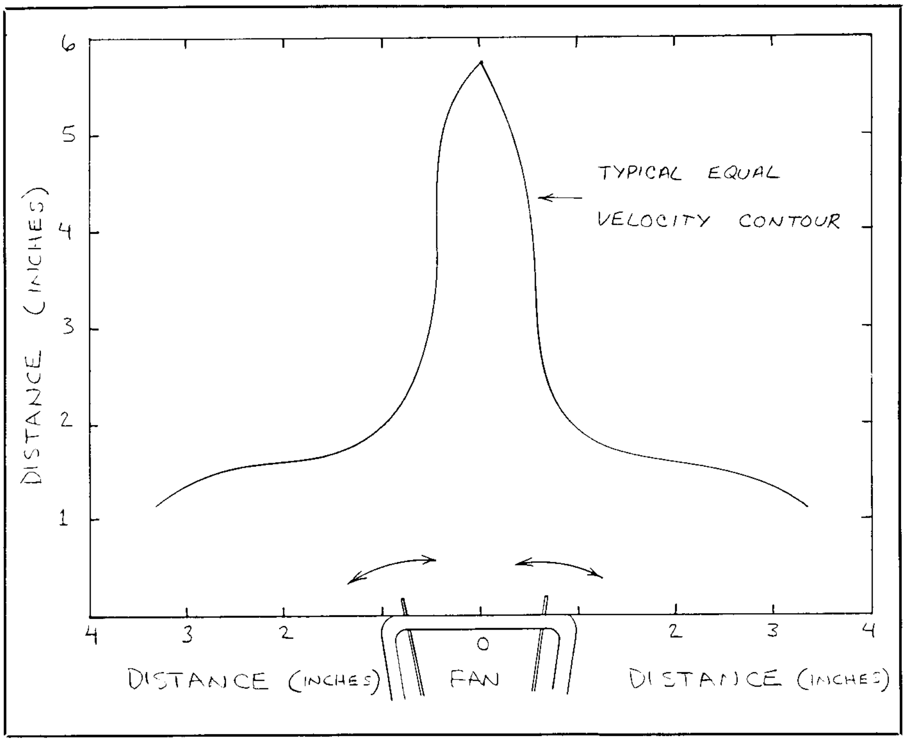

Fig. 7. Pattern of air movement from a Piezo Electric Products fan.

That is how I obtained the photos shown in Fig. 8.

For these photos, I mounted the fan on a small tripod, which I placed on a copy camera stand. Next, I directed two beams from a fiber-optic light source toward the vanes. I then adjusted the tripod so that the vanes diffusely reflected light from the fiber illuminator into the camera lens. As Fig. 9(B) reveals, the vibrating vanes of the powered-up fan are clearly visible.

Now about that requirement that the drive voltage have a sinusoidal wave shape. I connected my fan to a frequency generator through an ordinary 6.3-to-117-volt transformer to boost the voltage. The fan operated properly when the frequency of the generator was adjusted to near 60 Hz. It worked much better when the wave was square as opposed to when it was sinusoidal or triangular in shape.

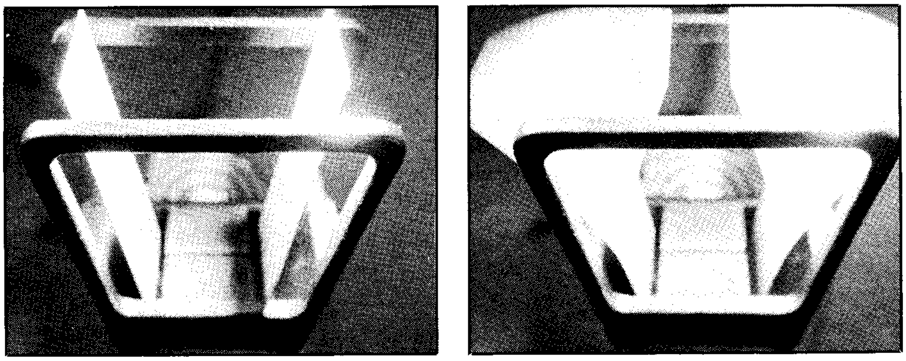

Fig. 8. The vanes of a piezoelectric fan with (A) no power and (B) power applied.

The sound from the fan operated from square waves also became considerably louder. The relatively loud buzzing noise may itself be sufficient reason to drive the fan with a quiet sinusoidal wave. Worse, the noise may indicate that the bender elements are being subjected to much more mechanical stress than they are designed to accommodate.

An interesting experiment is to alter the operating frequency of a piezoelectric fan. To do this, first connect the fan to a frequency generator through a step-up transformer. If you don't have a frequency generator, use any circuit that generates an adjustable-frequency sine or triangle waveform.

Next, cut a 2 by 8-centimeter rectangle from a paper index card. Draw a line across the rectangle 2 centimeters from one end. Attach a piece of double-sided clear adhesive tape to the marked end of the rectangle. Then carefully attach the rectangle to the end of one of the fan's Mylar vanes so that the line on the paper is even with the end of the vane. The vane is now 6 centimeters longer than its original length.

Now slowly increase the frequency of the signal applied to the fan. I found that the extended vane oscillated over very narrow frequency ranges centered around 12, 40, 125, 255, 300 and 425 Hz.

You can vary the length of the vane extension to obtain different results, of course. The easiest way to do this is to start with a 6-centimeter (or longer) extension and trim away segments with scissors. For example, I clipped the paper vane at the node produced when the fan was driven at 40 Hz. This shortened the vane by 2.2 centimeters and changed the resonant frequencies to 25, 65, 200, 300 and 450 Hz. The 200-Hz frequency was particularly noisy.

Going Further

Next month, we'll experiment with piezoelectric high-voltage trip hammers and sound disks. We'll also experiment with a remarkable piezoelectric plastic film. **ME**

Circuit Circus

By Charles D. Rakes

UNUSUAL USES FOR TRANSDUCERS

This month's Circus starts the new year off with a number of solid-state piezo-transducer circuits. Those critters can be heard chirping their little hearts out in just about every kind of equipment that uses an electronic sounder.

We wake up to the beep-beep sound of our digital clock. Then as we get into our automobile, a beep reminds us to buckle up. And on through the day we hear a beep here, a chirp there, directing our attention from one place to another. With all of the racket created by the piezo sounders, you'd think there's nothing else they can do. Well, it's just not so!

Fixed-Frequency Generator. The circuit shown in Fig. 1 is self-oscillating; in it, a piezo element is used as the frequency-determining component. The circuit produces a tone output that can be used as an encoding signal for remote control or any other application where a fixed-frequency tone signal is required.

An unusual function of that tone-encoding generator is that both an audible tone and a signal are generated at the same time. The circuit's operation is simple. A single op-amp (one fourth of an LM324 quad op-amp) is configured as a standard inverting amplifier.

At power-up, a positive voltage is applied to the non-inverting input of U1 (via R3), forcing its output high. That high travels along three paths. The first path is the tone output. Along the second path, by way of R5, that high is used as the drive signal for BZ1.

In the third path, the high output of U1 is fed back, via R4, to the inverting input of U1. That forces the output of U1 to go low. And that low, when fed back to the inverting input of U1, causes the op-amp output to again go high, and the cycle repeats itself. As configured, U1 provides a voltage gain of 4.7 (gain = R4/R1).

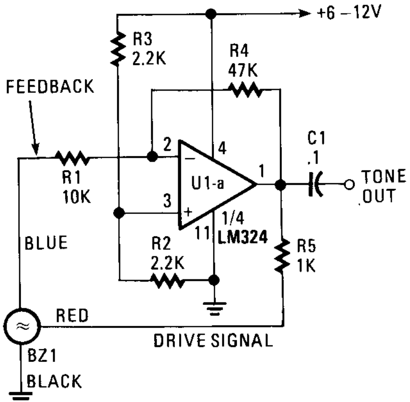

Fig. 1. This self-oscillating circuit uses a three-terminal piezo transducer as the frequency-determining component.

There are a number of "orphan" piezo transducers available on the surplus market. Several three-terminal piezo transducer elements were tried in the circuit and all performed well. The transducer specified in the Parts List comes with three short colored-coded (red, blue, and black) lead wires as indicated in Fig. 1. With the aid of the piezo-transducer pinout shown in Fig. 2, you should have little trouble in connecting any transducer to the circuit.

The outer ring of the piezo element is usually connected to circuit ground. The large, inner circle serves as the driven area, and the small, elongated section supplies the feedback signal. Resistor R5 sets BZ1's output-volume level. That level can be increased by decreasing R5 (say, to 470 ohms). To decrease the volume, increase R5 to about 2.2K, or so.

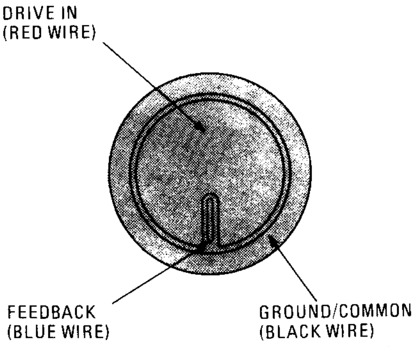

Fig. 2. Here is the pinout diagram for the three-terminal piezo transducer. The outer ring is usually connected to ground; the large inner circle is the driven area, and the elongated section is the feedback.

PARTS LIST FOR THE FIXED-FREQUENCY GENERATOR

U1—LM324 quad op-amp, integrated circuit
R1—10,000-ohm, ¼-watt, 5% resistor
R2, R3—2200-ohm, ¼-watt, 5% resistor
R4—47 000-ohm, ¼-watt, 5% resistor
R5—1000-ohm, ¼-watt, 5% resistor
C1—0.1-µF, ceramic disc capacitor
BZ1—Piezo fixed-frequency transducer, Radio Shack 273-064 or similar
Printed circuit or perfboard materials, enclosure, IC sockets, battery and battery holder, wire, solder, hardware, etc.

Resistors R2 and R3 set the bias for op-amp U1's positive input (pin 3) to half of the supply-voltage level. That allows for a maximum voltage swing at U1's output. Although a quad op-amp is specified in the Parts List, almost any similar low-cost single or dual op-amp will work for U1-a.

Sound-Activated Decoder. Turning our attention to Fig. 3, we see a piezo transducer performing double duty in that it operates as a sound-pickup device as well as a frequency-selective filter. Transducer BZ1, is connected to op-amp U1-a just as in the previous circuit, but with one notable exception—a gain control, potentiometer R3, has been added.

By controlling the gain of the op-amps, the oscillator circuit can be transformed into a sensitive and frequency-selective tone-decoder circuit. With the gain of U1-a set just below the point of self oscillation, the transducer becomes sensitive to acoustically coupled audio tones that occu at (or near) its resonant frequency.

The circuit's operation is compar
ble to an early and popular type
radio receiver in which regenerat
was used to achieve super-high gc
using relatively low-gain amplify
vacuum tubes. Regeneration is
tained by adding a controll
positive-feedback path betwee
receiver's input and output cir
And it was the gain obtained
generation in receivers of the
that turned a simple one-tube
a world-wide receiving statio

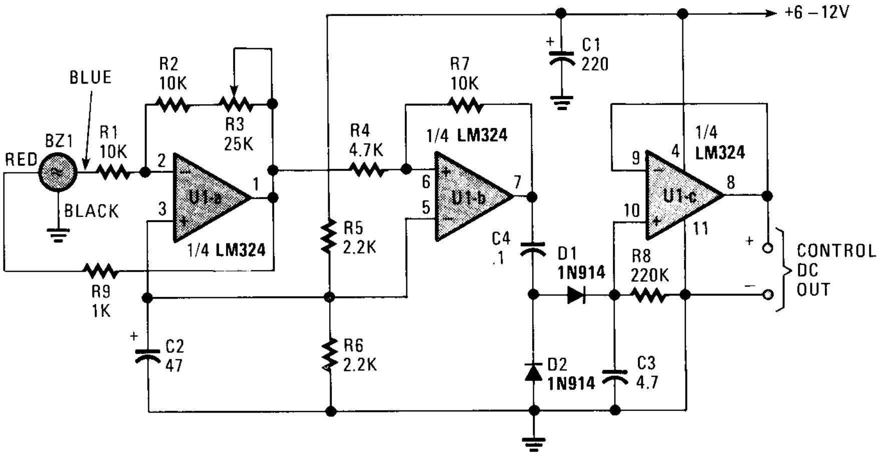

Fig. 3. In the Sound-Activated Decoder, the piezo transducer performs double duty, in that it operates as a sound-pickup device and a frequency-selective filter.

PARTS LIST FOR THE LOW-FREQUENCY CRYSTAL FILTER

U1—LM324 quad op-amp, integrated circuit
R1—47,000-ohm, ¼-watt, 5% resistor
R2–R5—10,000-ohm, ¼-watt, 5% resistor
R6, R7—2200-ohm, ¼-watt, 5% resistor
R8—100,000-ohm, ¼-watt, 5% resistor
C1, C2—0.1-µF ceramic-disc capacitor
C3—47-µF 16-WVDC electrolytic capacitor
C_X—See text
BZ1—Piezo transducer, Radio Shack #273-073 or similar
Printed circuit or perfboard materials, enclosure, IC sockets, battery and battery holder, wire, solder, hardware, etc.

PARTS LIST FOR THE SOUND-ACTIVATED DECODER

U1—LM324 quad op-amp, integrated circuit
D1, D2—1N914 general-purpose small-signal diode
R1, R2, R7—10,000-ohm, ¼-watt, 5% resistor
R3—25,000-ohm potentiometer
R4—4700-ohm, ¼-watt, 5% resistor
R5, R6—2200-ohm, ¼-watt, 5% resistor
R8—220,000-ohm, ¼-watt, 5% resistor
C1—220-µF, 25-WVDC electrolytic capacitor
C2—47-µF, 25-WVDC electrolytic capacitor
C3—4.7-µF, 25-WVDC electrolytic capacitor
C4—0.1-µF, ceramic-disc capacitor
BZ1—Piezo fixed-frequency transducer, Radio Shack #273-064 or similar
Printed circuit or perfboard materials, enclosure, IC sockets, battery and battery holder, wire, solder, hardware, etc.

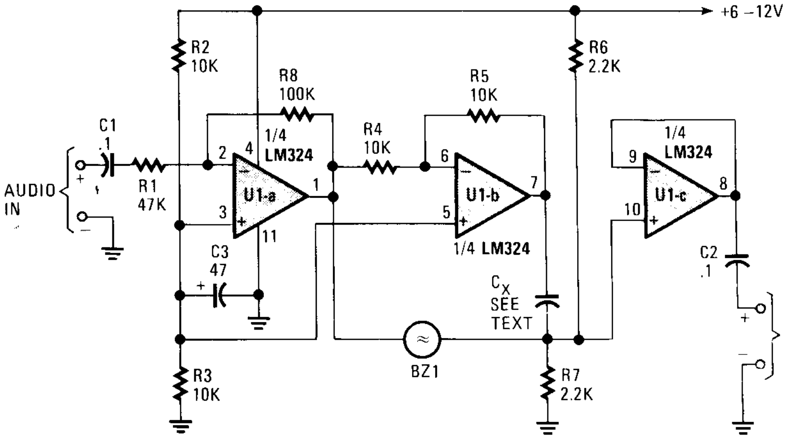

Fig. 4. In this circuit, the piezo transducer functions like a low-frequency, quartz crystal in a narrow band, crystal-filter circuit.

In-band audible tones reaching the transducer's surface cause the transducer to vibrate in step with the incoming sound wave. The regenerative action of the circuit then causes the signal to be amplified to a 1½- to 2-volt level. The output of U1-a is fed to U1-b, where the signal is doubled. The boosted signal is then fed across a dual-diode rectifier circuit to the input f a voltage follower, consisting of U1-c ly.

he circuit's output can be used to vate optocouplers, drive relay cir- or to control almost any DC-op- d circuit. The DC signal at the ıt of U1-c varies from zero to over ts, depending on the input-signal One unusual application for the d-Activated Decoder would be in extremely high-noise environments, where normal broadband microphone pickup would be useless. Because piezo transducers respond *only* to frequencies within a very narrow bandwidth, little if any of the noise would get through the transducer

Low-Frequency Crystal Filter. Another interesting job that the piezo transducer can perform is to function like a super low-frequency, quartz crystal in a narrow-band crystal-filter circuit. The circuit shown in Fig. 4 is the piezo equivalent of a super-selective crystal filter.

In a typical crystal-filter circuit, the crystal's internal capacitance is electronically canceled to keep unwanted and out-of-band signals from getting through and showing up at the filter's output. Internal capacitance normally runs in the low picofarad range for crystals and in the 20- to 30,000-pF range for the piezo transducers.

In a quartz circuit, a small trimmer capacitor is used to tweak out the capacitance effect, but to use the same approach for the piezo filter, you'd need to gang at least 100 broadcast-band tuning capacitors together to achieve the same effect.

With our piezo-transducer circuit, op-amp U1-a doubles the level of the input signal. That magnified signal is fed to one leg of BZ1, while at the same time being fed to the inverting input of U1-b. Op-amp U1-b, with a voltage gain of one, inverts the signal's waveform, which is next fed through capacitor C_X and then to the other side of the piezo element.

If the value of C_X equals the internal capacitance of the piezo element, the transducer's capacitance effect is canceled out. Several piezo transducers come with a list of their electrical characteristics, including their internal-capacitance figure. If the information isn't available, it can be determined with the aid of a capacitance decade-box or a capacitance meter.

(Continued on page 97)