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Frequency Control Devices

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I. Introduction

Frequency control devices provide the precise time and frequency on which modern electronics depends. A vibrating quartz crystal, i.e., a quartz resonator, is the "heart" of nearly all frequency control devices. Quartz clocks provide accurate time and quartz oscillators are the sources of precise frequency.

The fundamental roles these devices play in the modern world can be seen by considering what would happen if all the quartz crystals in the world suddenly stopped vibrating. All modern communication systems (telephones, radios, TV stations, air traffic control systems, etc.) would stop functioning, all but the oldest transportation systems (automobiles, trucks, airplanes) would cease operating, and all computers would stop. The consequences would be catastrophic.

Time is important not only for the daily schedules of human beings, but also, for example, for determining the sequence of events that take place inside computers, and for time-tagging the information that flows through communication systems. Frequency sources are essential for determining the frequencies of radio and TV transmissions, radar systems, communication and navigation systems, etc.

Frequency control technology took a great leap forward in the 1920s when quartz was first utilized to realize crystal resonators for the stabilization of oscillators, thereby launching the field of modern frequency control. With the introduction of quartz control, timekeeping moved from the sun and stars to small, man-made sources that exceeded astronomy-based references in stability. Since then, the applications of devices based on quartz have expanded dramatically. The quartz resonator has continued to evolve to become a device capable of precision one million times greater than the original. It also serves as the "flywheel" in atomic frequency standards. Atomic standards make frequency the most accurate entity known.

Of the man-grown single crystals, quartz is second to silicon in quantity grown. About 2500 to 3000 tons of quartz crystals are grown per year (about three to four times as much silicon is grown). The major applications are oscillators for clocks and frequency sources. Other important applications are sensors, and filters used for frequency selection. About 2×10^9 bulk acoustic wave (BAW) quartz resonators, and several hundred million quartz surface acoustive wave (SAW) devices are manufactured annually.

II. Applications

The major applications of quartz crystals are shown in Table 1. The applications in the fourth and fifth columns comprise most of the annual production, but the applications in the first and second columns are the most demanding.

The military applications have been, and continue to be, the "drivers" of the technology. Civilian applications usually follow at a later date. For example, the military developed spread-spectrum techniques for jamming resistance and communication security. Civilian applications of spread-spectrum technology followed, such as the cellular telephone systems in

TABLE 1

MAJOR APPLICATIONS OF QUARTZ CRYSTALS

Military and Aerospace	Research and Metrology	Industrial	Consumer	Automotive
Communications	Atomic clocks	Communications	Watches and clocks	Engine control, stereo, clock
Navigation	Instruments	Telecommunications	Cellular and cordless phones, pagers	Trip computer
IFF	Astronomy and geodesy	Mobile/cellular/portable radio, telephone and pager	Radio and hi-fi equipment	
Radar	Space tracking	Aviation	Color TV	
Sensors	Celestial navigation	Marine	Cable TV systems	
Guidance systems		Navigation	Home computers	
Fuzes		Instrumentation	VCR and video camera	
Electronic warfare		Computers	CB and amateur radio	
Sonobuoys		Digital systems	Toys and games	
		CRT displays	Pacemakers	
		Disk drives		
		Modems		
		Tagging/identification		
		Utilities		

which spread-spectrum techniques are used for maximizing the number of simultaneous users in the assigned frequency band.

In the United States, the genesis of the quartz crystal industry can be traced to the decision in 1939 to make large-scale use of crystal control in military communication systems [1]. In early military systems, controlling the carrier frequency of radio communications systems was the primary application. The typical (normalized frequency) accuracy in World War II systems was 200 ppm [2]. In systems of the 1960s and 1970s, the typical accuracy requirements ranged from 40 to 0.5 ppm [3]. In systems that are currently in production or development, the accuracy requirements range from 5 ppm in some tactical radios to parts in 10^{12} in some navigation, electronic warfare, and strategic communication systems. In addition to possessing high accuracy, the frequency sources of modern systems must also exhibit low noise characteristics and must remain stable in extreme environments.

In the following section, the most demanding applications are reviewed. Many of these are military applications; some of these have parallels in the civilian world.

In early military systems, controlling the carrier frequency for improved spectrum utilization was the principal driver of frequency control technology. In modern systems, the major drivers are spread-spectrum systems that require ever-higher clock accuracies, surveillance systems that require low-noise oscillators in the presence of platform vibrations, and tactical (hand-held) systems that require ever-higher accuracies with the lowest possible battery consumption and in the smallest possible volume.

A. Communication Systems

In communication systems, the accuracy and stability of oscillators and clocks affect important system performance parameters, such as the spectrum utilization, resistance to unintentional and intentional (i.e., jamming) interference, signal acquisition speed, autonomy period, and bit error rates.

1. *Spectrum Utilization*

In the field of communications electronics, the subject of frequency control is intimately related to the subject of frequency spectrum utilization [4]. Historically, in both commercial and military systems, to allow for more users in a given frequency band, it was necessary to reduce the channel spacings, which required the tightening of the frequency tolerances allowed in both the transmitters and receivers. As the number of users grew, and as technology allowed the allocation of higher frequency bands, the frequency tolerances became tighter and tighter. The same channel spacing at a higher frequency, of course, requires tighter frequency tolerance. The frequency accuracy requirements of tactical radios prior to the advent of spread-spectrum techniques were typically 10 to 50 ppm. Radios that employ spread-spectrum techniques typically require 5- to 0.001-ppm oscillators. In digital communication systems, not only must the oscillators possess high accuracy, they must also have low noise characteristics, for reasons that are discussed below.

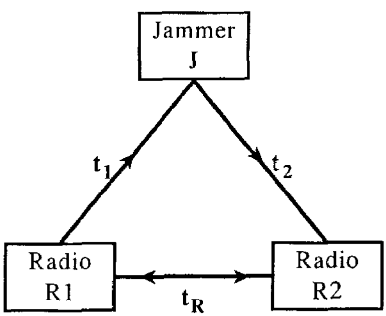
The noise of oscillators can also limit the capacity of communication systems. Since the noise from a transmitter in one channel extends to neighboring channels, as the number of transmitters grows, the noise accumulates to the point where receivers can no longer function properly. For example, in one L-band satellite communication system, the vibration-induced phase noise [5, 6] is a serious limitation on the number of users per transponder when the users are on vibrating platforms, such as aircraft, trucks, etc. The noise from a typical commercial oscillator (2×10^{-9} per g vibration sensitivity) limits the number of users to less than 100 per transponder, whereas a state-of-the-art oscillator (2×10^{-10} per g vibration sensitivity) can allow as many as 1200 users per transponder. Since the rental of a transponder costs more than $1 million per year, the economic impact of oscillator noise can be significant [7].

2. *Resistance to Jamming*

Spread-spectrum techniques are used in military systems primarily for rejecting intentional and unintentional jamming, and for communication security [8, 9]. In spread-spectrum systems, the transmitters and receivers contain clocks that must be synchronized. For example, frequency hopping is a spread-spectrum technique used in several evolving military communication systems. In such systems, the transmitters and receivers must hop to the same frequency at the same time. The faster the hopping rate, the higher the jamming resistance, and the more accurate the clocks must be. For example, for a system with a hopping rate of 1000 hops per second, the dwell time at each frequency is 1 millisecond. For such a system to operate properly, the clocks must remain synchronized to about 100 microseconds.

When several radio nets operate in an area, self-jamming can be a problem if the nets operate independently of one another, i.e., if the nets are not orthogonal. Radios of neighboring nets can then occasionally hop to the same frequency at the same time, thus producing self-jamming. When the nets are orthogonal, i.e., when the neighboring nets are synchronized and use codes that ensure that radios do not hop to the same frequency at the same time, the radios must not only be synchronized within a net but also to those of neighboring nets. This requires an even higher clock accuracy.

With the availability of fast spectrum analyzers and synthesizers, it is possible to jam frequency hopping systems [9, 10]. If the jammer is fast enough, it can detect the frequency of transmission and tune the jammer to that frequency well before the radio hops to the next frequency. However, with a good enough clock, it is possible to defeat such follower jamming. As is illustrated in Fig. 1, even a "perfect" follower jammer can be defeated if a good enough clock is available to allow a very fast hop rate. (A perfect jammer is defined as one that can identify the frequency of a received signal, tune a synthesizer to that frequency, and transmit the jamming signal in zero time.) Because radio waves travel at the speed of light, the radio-to-jammer-to-radio (R1 to J to R2) and radio-to-radio (R1 to R2) propagation delays are 3.3 μs per km. Therefore, if the hop-rate is fast enough for the propagation delay difference to be greater than 1/hop-rate, i.e., if the radios can hop to the



To defeat a "perfect" follower jammer, need a hop-rate given by:

$$t_m < (t_1 + t_2) - t_R,$$

where $t_m \approx$ msg. duration/hop $\approx$ 1/hop-rate

Example

Let R1 to R2 = 1 km, R1 to J = 5 km, and J to R2 = 5 km. Then, since propagation delay = 3.3 μs/km, $t_1 = t_2 = 16.5$ μs, $t_R = 3.3$ μs, and $t_m < 30$ μs.

Allowed clock error $\approx 0.2\ t_m \approx 6$ μs.

For a 4 hour resynch interval, clock accuracy requirement is: $\mathbf{4 \times 10^{-10}}$

FIG. 1. Clock required for a jamming-proof very fast frequency hopping radio.

next frequency before the jamming signal reaches the receiver, then the radios are jamming-proof (for follower jammers). In the example of Fig. 1, the propagation delays t_1, t_2, and t_R imply that the message duration t_m must be less than 30 μs. Since the clock accuracies required by frequency hopping systems are usually 10 to 20% of t_m, the allowed clock error is about 6 μs. In a military environment, such accuracies can be maintained for periods of hours and longer only with atomic clocks.

The requirement for C^3 systems to be interoperable places yet another stringent requirement on accuracy. For example, when an Army unit calls for air support from an Air Force unit that may be many hundreds of kilometers away, the clocks in the respective units' radios must be synchronized for the units to be able to communicate. Maintaining synchronization for extended periods among independent clocks that are widely separated requires very high quality clocks.

3. Signal Acquisition Speed

The speed with which a communication link can be established depends on the speed with which a transmitter's signal can be acquired, which is strongly dependent on the frequency difference between transmitter and receiver [11]. In spread-spectrum systems, it is also dependent on the time difference between the transmitter's clock and the receiver's clock. The larger these differences, the longer it takes to search and acquire. While searching, the system is more vulnerable to interception and jamming than at other times. For acquiring weak signals, the noise of the receiver's reference oscillator can also affect the acquisition.

For example, in a tactical radio system, the time it takes for a radio to enter a net depends on the radio's frequency and time errors. Similarly, in a satellite communication system, the time it takes for a terminal to acquire the satellite depends on the terminal's frequency and time errors. (Range errors also affect the relative time between transmitter and receiver.) In a navigation system, such as the Global Positioning System (GPS), the time to first fix is strongly dependent on the receiver's frequency error [12]. Minimizing acquisition time is especially important in submarine and special operations forces electronic systems, because avoiding detection is of paramount importance in such systems. In secure communication systems, precise synchronization and low noise is necessary to be able to recover encrypted data.

4. *Autonomy Period*

Autonomy period, also called "radio silence interval," is important in modern warfare. For example, to remain undetected, submarine and special operations forces must, at times, refrain from communicating over the air for extended periods. When clocks are not resynchronized and resyntonized (i.e., re-frequency calibrated), time and frequency errors increase with increasing mission duration. The better the long-term stability of the systems' oscillators, the longer can be the allowable autonomy period, and the shorter will be the subsequent acquisition time.

5. *Digital Communications*

Digital communication systems, whether commercial or military, must be synchronized and have the same data rates. Synchronization plays a critical role in such systems because it ensures that information transfer is performed with minimal buffer overflow or underflow events, i.e., with an acceptable level of "slips." Slips cause problems, e.g., missing lines in FAX transmission, clicks in voice transmission, loss of encryption key in secure voice transmission, and data retransmission [13, 14].

The phase noise of oscillators can lead to erroneous detection of phase transitions, i.e., to bit errors, when phase-shift-keyed (PSK) digital modulation is used. In digital communications, for example, where 8-ary PSK is used, the maximum phase tolerance is $\pm 22.5^\circ$, of which $\pm 7.5^\circ$ is the typical allowable carrier noise contribution [14]. Due to the statistical nature of phase deviations, if the RMS phase deviation is 1.5°, for example, the probability of exceeding the $\pm 7.5^\circ$ phase deviation is 6×10^{-7}, which can result in a bit error rate that is significant in some applications.

Shock and vibration can produce large phase deviations even in "low-noise" oscillators [5, 6]. Moreover, when the frequency of an oscillator is multiplied by N, the phase deviations are also multiplied by N. For example, a phase deviation of 10^{-3} radian at 10 MHz becomes 1 radian at 10 GHz. Such large phase excursions can be catastrophic to the performance of systems, e.g., those that rely on phase locked loops (PLL) or phase sift keying. Low-noise, acceleration-insensitive oscillators are essential in such applications.

B. NAVIGATION

Precise time is essential to precise navigation. Historically, navigation has been a principal motivator in man's search for better clocks. Even in ancient times, one could measure latitude by observing the stars' positions, but determining longitude is a problem of timing. Since the earth makes one revolution in 24 hours, one can determine longitude from the time difference, Δt, between local time (which was determined from the sun's position) and the time at the Greenwich meridian (which was determined by a clock): longitude in degrees $= (360^\circ/24 \text{ hours}) \times \Delta t$ in hours.

Today's military (and civilian) navigation systems require ever-greater accuracies. Modern navigation systems utilize ultraprecise clocks and radio transmissions of precisely timed navigation signals. The Global Positioning System (GPS), developed by the U.S. Department of Defense, is the most accurate worldwide navigation system available. As the price of GPS receivers has declined, the number of civilian applications of GPS has increased. Today, the number of GPS receivers sold for civilian applications far exceeds the military sales.

In GPS, navigation is accomplished by one-way time measurements [15–18]. Since electromagnetic waves travel 0.3 meters (i.e., a foot) per nanosecond,, if, for example, a vessel's timing was in error by a microsecond, a navigational error of 300 meters would result. In GPS, atomic clocks in the satellites and quartz oscillators in the receivers provide nanosecond-level accuracies. The resulting (worldwide) navigational accuracies are about 10 meters and differential accuracies can be as good as a few millimeters.

Each GPS spacecraft contains four high-performance atomic clocks. (Only one is turned on; the others are for backup.) The military GPS receivers contain oven-controlled crystal oscillators (OCXO); the less expensive commercial receivers contain less expensive temperature-compensated crystal oscillators (TCXO). The spacecraft clocks provide a time accuracy of better than 100 nanoseconds [17, 18]. The oscillator is a key component in the receiver [12]. In military receivers, especially, the oscillator's performance has a direct influence on system performance. The noise of the oscillator affects the navigation accuracy and the performance (i.e., jamming margin) in a high-jamming environment; the medium-term (10 to 1000 second) stability affects the reacquisition capability, system integrity monitoring, and performance in a high-jamming environment; the long-term stability affects the time to subsequent fix and the capability to operate with less than four satellites; the warm-up time of the oscillator affects the time to first fix; and the power requirement and the size of the oscillator affect the receiver's battery life, mission duration, and weight.

C. Surveillance

In surveillance, Doppler radars especially require low-noise oscillators [19, 20]. The velocity of the target and the radar frequency are primary determinants of the phase noise requirements. Slow-moving targets produce small Doppler shifts, therefore, low phase noise close to the carrier is required. To detect fast-moving targets, low noise far from the carrier is required. For example, when using an X-band radar to detect a 4 km/hour target (e.g., a slowly moving vehicle), the noise 70 Hz from the carrier is the important parameter, whereas to detect supersonic aircraft, the noise beyond 10 kHz is important.

When a radar is on a stationary platform, the phase noise requirements can usually be met with commercially available oscillators. A good quartz crystal (bulk acoustic wave, BAW) oscillator can provide sufficiently low noise close to the carrier, and a good surface acoustic wave (SAW) oscillator can provide sufficiently low noise far from the carrier [21]. Very far from the carrier, dielectric resonator oscillators (DRO) can provide lower noise than either BAW or SAW oscillators. A combination of oscillators can be used to achieve good performance in multiple spectral regions [22], e.g., a DRO phase locked to a frequency-multiplied BAW oscillator can provide low noise both close to the carrier and far from the carrier.

The problem with achieving sufficiently low phase noise occurs when the radar platform vibrates, as is the case when the platform is an aircraft or a missile [5, 6]. The vibration applies time-dependent stresses to the resonator in the oscillator, which results in modulation of the output frequency. The aircraft's random vibration thereby degrades the phase noise, and discrete frequency vibrations (e.g., due to helicopter blade rotation) produce spectral lines that can result in false target indications. The degradation in noise spectrum occurs in all types of oscillators (BAW, SAW, DRO, atomic frequency standards, etc.) Figure 2 shows an example of a typical aircraft random vibration envelope (in the upper right-hand corner) and the resulting phase noise degradation [5, 6]. Such a large degradation can have catastrophic effects on radar performance. In a coherent radar, the platform-vibration-induced phase noise can reduce the probability of detection to zero.

Most air defense systems cannot cope with stealth aircraft. To detect stealthy targets, the radar systems must compensate for the smaller reflections by significantly increasing the transmitted power, which is often not feasible, or by significantly improving the radar receiver's sensitivity. Higher sensitivity results in receiving more clutter and false targets. Very low noise reference oscillators are required for detecting targets under such conditions.

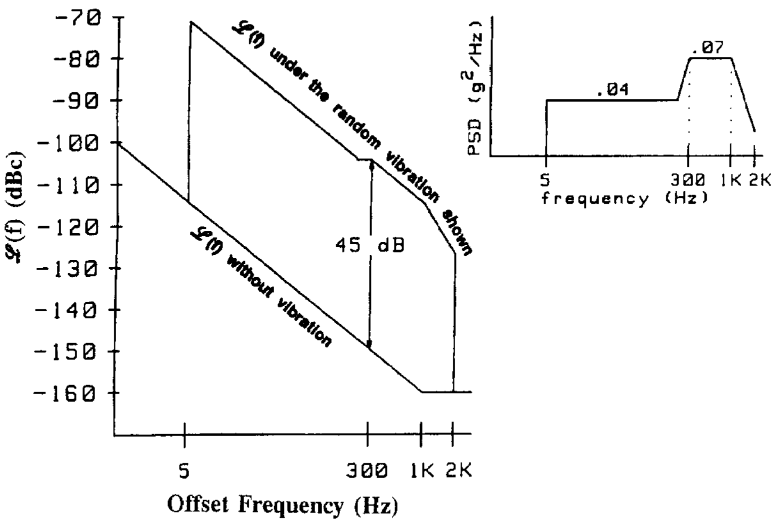


FIG. 2. A typical aircraft random vibration envelope (in the upper right-hand corner), and the resulting phase noise degradation.

Conventional (i.e., "monostatic") radar, in which the illuminator and receiver are on the same platform, is vulnerable to a variety of countermeasures. Bistatic radar [23], in which the illuminator and receiver are widely separated, can greatly reduce the vulnerability to countermeasures such as jamming and antiradiation weapons. The transmitter can remain far from the battle area, in a "sanctuary." The receiver can remain "quiet."

The timing and phase coherence problems can be orders of magnitude more severe in bistatic than in monostatic radar, especially when the platforms are moving. The two reference oscillators must remain synchronized and syntonized during a mission so that the receiver knows when the transmitter emits each pulse, and so that the phase variations will be small enough to allow a satisfactory image to be formed. Low-noise crystal oscillators are required for short-term stability; atomic frequency standards are often required for long-term stability. (A combination of a low-noise crystal oscillator and an atomic standard can provide both low noise and good long-term stability.)

D. IDENTIFICATION-FRIEND-OR-FOE (IFF) SYSTEMS

In modern warfare, when the sky is filled with friendly and enemy aircraft, and a variety of advanced weapons are ready to fire from both ground and airborne platforms, reliable identification of friend and foe is critically important. Friendly-fire casualties due to lack of adequate IFF systems have been a major problem in recent wars [24]. Precise timing can play a major role in solving this problem. For example, cooperative IFF systems use an interrogation/response method that employs cryptographically encoded spread-spectrum signals. The interrogation signal received by a friend is supposed to result in the "correct" code being automatically sent back via a transponder on the friendly platform. The "correct" code must be changed frequently to prevent a foe from recording and transmitting that code ("repeat jamming"), thereby appearing to be a friend. The code is changed at the end of what is called the code validity interval, (CV).

The better the clock accuracy, the shorter can be the CVI, the more resistant the system can be to repeat jamming, and the longer can be the autonomy period for users who cannot resynchronize their clocks during a mission. The CVI chosen is usually dictated by the accuracies achievable with low-power oscillators.

E. Electronic Warfare

The ability to locate radio emitters is important in modern warfare. One method of locating emitters is to measure the time difference of arrival of the same signal at widely separated locations. Emitter location by means of this method depends on the availability of highly accurate clocks, and on highly accurate methods of synchronizing clocks that are widely separated. Since electromagnetic waves travel at the speed of light (30 cm per nanosecond), the clocks of emitter-locating systems must be kept synchronized to within nanoseconds to locate emitters with high accuracy. (Multipath and the geometrical arrangement of emitter locators usually result in a dilution of precision.) Without resynchronization, even the best available militarized atomic clocks can maintain such accuracies for periods of only a few hours. With the availability of GPS and using the "GPS common view" method of time transfer, widely separated clocks can be synchronized to better than 10 ns [17]. An even more accurate method of synchronization is "two-way time transfer via communication satellites," which, by means of very small aperture terminals (VSATs) and pseudonoise modems, can attain subnanosecond time transfer accuracies [25].

An important application for frequency sources is the ELINT (ELectronic INTelligence) receiver. These receivers are used to search a broad range of frequencies for signals that may be emitted by a potential adversary. The frequency source must be as noise-free as possible so as not to obscure weak incoming signals. The frequency source must also be extremely stable and accurate to allow accurate measurement of the incoming signal's characteristics.

F. Missile Guidance

When a missile is guided by ground radar, the radar is vulnerable to antiradiation missiles and other countermeasures. Placing the radar on-board the missile can greatly reduce the vulnerability, but at the expense of placing much greater demands on missile components, especially the reference oscillator. As previously discussed, the missile's high vibration levels degrade the oscillator phase noise by a wide margin. Vibration-insensitive low-noise oscillators are required for on-board radar systems. Such systems could benefit greatly from improvements in vibration-resistant low-noise oscillators [5].

G. Battery Consumption

Tactical military electronic systems are usually powered by batteries. In many of these systems, precise timing plays an essential role. When the system is not being used, everything except the clock can usually be turned off. As a result, the power requirement of the clock is a major determinant of battery consumption. For example, to power the time and frequency unit in one tactical satellite terminal during the required 10-day standby period, a battery pack weighing 18 kg was required. By replacing the power-hungry, oven-controlled crystal oscillator of the original design with a Microcomputer Compensated Crystal Oscillator (MCXO) [26], which is a much lower power oscillator of similar accuracy, 12 kg of battery weight could be saved.

The cost savings resulting from reducing the power requirements of oscillators can be large. For example, a calculation estimates that for one model of tactical radio, the cost savings resulting from reducing the power requirement for the radio's 20-year life, (assuming peace-time usage of 2 hours per day) is $48,000 per milliwatt per 10,000 radios [27]. Since more than 200,000 of these radios may eventually be produced, the eventual cost savings when this radio is fully fielded may be more than $1 million per mW of power saving! During a conflict, the radios would, of course, be used 24 hours per day, for an even greater saving; however, the real benefit of lower power radios is a lighter, more mobile force, which can operate for longer periods without needing battery replenishment.

Another reason for minimizing the power dissipation of oscillators is that the dissipation often produces undesirably large infrared signatures, which makes the system easier to detect by an adversary.

H. Survivability under Radiation and High Acceleration

Survivability under ionizing radiation and high shock and vibration conditions is primarily a military (and space) requirement. Gun-hardened oscillators are required, for example, for smart munitions, air-dropped and artillery-emplaced sensors, fuzes, and space defense systems. The highly shock-resistant oscillators have been developed that can withstand the shock of being launched from a howitzer [28, 29]. Radiation-hardening of oscillators used to be a major issue in many military systems because a high-intensity pulse of nuclear radiation stops clocks and causes large temporary, and smaller permanent, frequency offsets in frequency standards [30]. With the threat of nuclear war receding, radiation-hardening is less of an issue today for military systems (although it remains an important issue for space systems).

I. Logistics Costs

The long-term stability and the lifetime of oscillators often have a significant impact on logistics costs. As the oscillator's frequency ages (and all but cesium beam frequency standards do age), or as, e.g., a cesium beam frequency standard nears end of life, at some point, the oscillators must be recalibrated or replaced. A need for frequent recalibration or replacement has a significant adverse impact on the life cycle cost of equipment. Lower aging oscillators do cost more initially; however, the increased cost is often recovered rapidly through a decrease in logistics costs. An important goal of research aimed at reducing oscillator aging is to provide systems with calibration-free life.

III. Frequency Control Device Fundamentals

The fundamentals of quartz oscillators are reviewed in this section, with emphasis on quartz frequency standards (as opposed to inexpensive clock oscillators). The subjects discussed include: crystal resonators and oscillators, oscillator types, and the characteristics and limitations of temperature-compensated crystal oscillators (TCXO) and oven-controlled crystal oscillators (OCXO). The oscillator instabilities discussed include: aging, noise, frequency vs temperature, warm-up, acceleration effects, magnetic-field effects, radiation effects, and atmospheric pressure effects. Interactions among the various effects are also considered. Guidelines are provided for oscillator comparison and selection. Discussions of specifications are also included, as are references and suggestions for further reading.

A. Crystal Oscillators

1. Oscillator Basics

Figure 3 is a greatly simplified circuit diagram that shows the basic elements of a crystal oscillator [31–33]. The amplifier of a crystal oscillator consists of at least one active device and the necessary biasing networks; it may also include other elements for band limiting, impedance matching, and gain control. The feedback network consists of the crystal resonator and may contain other elements, such as a variable capacitor for tuning.

The frequency of oscillation is determined by the requirement that the closed-loop phase shift equal $2n\pi$, where n is an integer, usually 0 or 1. When the oscillator is initially energized, the only signal in the circuit is noise. That component of noise, the frequency of which satisfies the phase condition for oscillation, is propagated around the loop with increasing amplitude. The rate of increase depends on the excess loop gain and on the bandwidth of the crystal network. The amplitude continues to increase until the amplifier gain

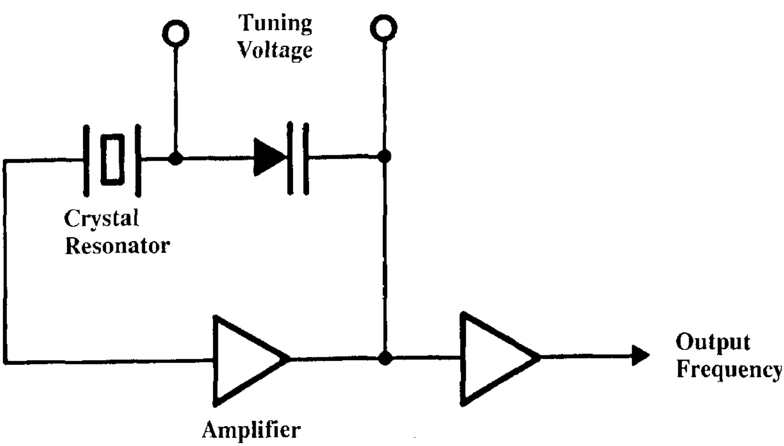


FIG. 3. Crystal oscillator — simplified circuit diagram.

is reduced, either by the nonlinearities of the active elements (in which case it is *self-limiting*) or by an external level-control method.

At steady state, the closed-loop gain is 1. If a phase perturbation $\Delta\phi$ occurs, the frequency of oscillator must shift by a Δf to maintain the $2n\pi$ phase condition. It can be shown that for a series-resonance oscillator

$$\frac{\Delta f}{f} = -\frac{\Delta\phi}{2Q_L},$$

where Q_L is the loaded Q of the crystal in the network [31]. ("Crystal" and "resonator" are often used interchangeably with "crystal unit," although "crystal unit" is the official name. See references 3 to 6 for further information about crystal units.) Crystal oscillator design information can be found in references 31, 32, 35, and 36. The abbreviation for crystal oscillator is XO.

2. *Crystal Unit Equivalent Circuit*

A quartz crystal unit is a quartz wafer to which electrodes have been applied, and which is hermetically sealed in a holder structure. (The wafer is often referred to as the "blank," or the "crystal plate.") Although the design and fabrication of crystal units comprise a complex subject, the oscillator designer can treat the crystal unit as a circuit component and just deal with the crystal unit's equivalent circuit.

The mechanically vibrating system and the circuit shown in Fig. 4 are "equivalent," because each can be described by the same differential equation

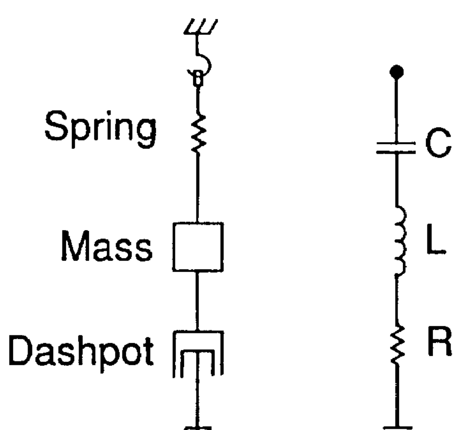


FIG. 4. Equivalent circuit of a mechanically vibrating system.

[37]. The mass, spring, and damping element (i.e., the dashpot) correspond to the inductor, capacitor, and resistor. The driving force corresponds to the voltage, the displacement of the mass to the charge on the capacitor, and the velocity to the current.

A crystal resonator is a mechanically vibrating system that is linked, via the piezoelectric effect, to the electrical world. Figure 5 shows a (simplified) equivalent circuit (of one mode of vibration) of a resonator, together with the circuit symbol for a crystal unit. A load capacitor C_L is shown in series with the crystal. C_0, called the "shunt" capacitance, is the capacitance due to the electrodes on the crystal plate plus the stray capacitances due to the crystal enclosure. The R_1, L_1, C_1 portion of the circuit is the "motional arm," which arises from the mechanical vibrations of the crystal.

The C_0 to C_1 ratio is a measure of the interconversion between electrical and mechanical energy stored in the crystal, i.e., of the piezoelectric coupling factor, k. C_0/C_1 increases with the square of the overtone number; the relationship of C_0/C_1 to k and N is $2C_0/C_1 = [\pi N/2k]^2$, where N is the overtone number. When a dc voltage is applied to the electrodes of a resonator, the capacitance ratio C_0/C_1 is also a measure of the ratio of electrical energy stored in the capacitor formed by the electrodes to the energy stored elastically in the crystal due to the lattice strains produced by the piezoelectric effect. Figure 6 shows the reactance versus frequency characteristic of the crystal unit. The C_0/C_1 is also inversely proportional to the

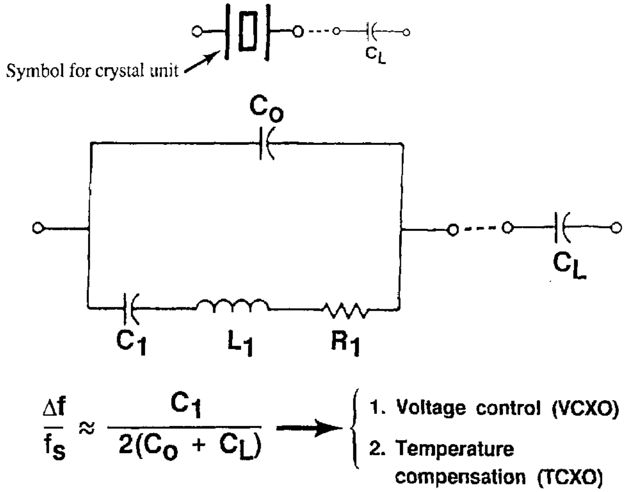


FIG. 5. Equivalent circuit of crystal unit with load capacitor.

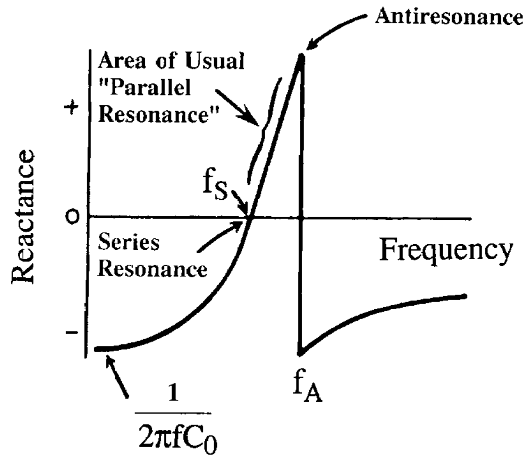


FIG. 6. Reactance versus frequency of a crystal unit.

antiresonance–resonance frequency separation (i.e., the pole-zero spacing), which is an especially important parameter in filter applications. The slope of the reactance vs frequency curve near f_s is inversely proportional to C_1, i.e., $\Delta X/(\Delta f/f) \sim 1/\pi f C_1$ near f_s, where X is the reactance. C_1 is, therefore, a measure of the crystal's "stiffness," i.e., its tunability—see the next equation.

When the load capacitor is connected in series with the crystal, the frequency of operation of the oscillator is increased by a $\Delta f'$, where $\Delta f'$ is given by

$$\frac{\Delta f'}{f} = \frac{C_1}{2(C_0 + C_L)}.$$

When an inductor is connected in series with the crystal, the frequency of operation is decreased. The ability to change the frequency of operation by adding or changing a reactance allows for compensation of the frequency vs temperature variations of crystal units in TCXOs and for tuning the output frequency of voltage-controlled crystal oscillators (VCXO); in both, the frequency can be changed by changing the voltage on a varactor.

For the simple *RLC* circuit of Fig. 4, the width of the resonance curve is inversely proportional to the quality factor Q, but in a crystal oscillator, the situation is complicated by the presence of C_0 and by the fact that the operating Q is lower than the resonator Q. For a quartz resonator, $Q = (2\pi f_s C_1 R_1)^{-1}$. References 3, 5, and 6 contain further details on the equivalent circuit.

Some of the numerous advantages of a quartz crystal resonator over a tank circuit built from discrete *R*s, *C*s, and *L*s are that the crystal is far stiffer and has a far higher Q than what could be built from normal discrete components. For example, a 5-MHz fundamental mode AT-cut crystal may have $C_1 = 0.01$ pF, $L_1 = 0.1$ H, $R_1 = 5\,\Omega$, and $Q = 10^6$. A 0.01-pF capacitor is not available, since the leads attached to such a capacitor would alone probably contribute more than 0.01 pF. Similarly, a 0.1-H inductor would be physically large, would need to include a large number of turns, and would need to be superconducting to have a resistance $\leq 5\,\Omega$.

3. *Stability versus Tunability*

In most crystal oscillator types, a variable-load capacitor is used to adjust the frequency of oscillation to the desired value. Such oscillators operate at the parallel resonance region of Fig. 5, where the reactance vs frequency slope (i.e., the "stiffness") is inversely proportional to C_1. For maximum frequency stability with respect to reactance (or phase) perturbations in the oscillator circuit, the reactance slope (or phase slope) must be maximum. This requires that the C_1 be minimum. The smaller the C_1, however, the more difficult it is to tune the oscillator (i.e., the smaller is $\Delta f'$ for a given change in C_L). The highest stability oscillators use crystal units that have a small C_1 (and a high Q). Since C_1 decreases rapidly with overtone number, high-stability oscillators generally use third- or fifth-overtone crystal units. Overtones higher than fifth are rarely used, because R_1 also increases rapidly with overtone number, and some tunability is usually desirable to allow setting the oscillator to the desired frequency.

Wide-tuning-range VCXOs use fundamental mode crystal units of large C_1. Voltage control is used for the following purposes: to frequency or phase lock two oscillators; for frequency modulation; for compensation, as in a TCXO (see below); and for calibration (i.e., for adjusting the frequency to compensate for aging). Whereas a high-stability, ovenized 10-MHz VCXO may have a frequency adjustment range of $\pm 5 \times 10^{-7}$ and an aging rate of 2×10^{-8} per year, a wide-tuning-range 10-MHz VCXO may have a tuning range of ± 50 parts per million (ppm) and an aging rate of 2 ppm per year.

In general, making an oscillator tunable over a wide frequency range degrades its stability because making an oscillator susceptible to intentional tuning also makes it susceptible to factors that result in unintentional tuning. For example, if an oven-controlled crystal oscillator (OCXO) is designed to have a stability of 1×10^{-12} for a particular averaging time and a tunability of

1×10^{-7}, then the crystal's load reactance must be stable to 1×10^{-5} for that averaging time. Achieving such load-reactance stability is difficult because the load-reactance is affected by stray capacitances and inductances, by the stability of the varactor's capacitance vs voltage characteristic, and by the stability of the voltage on the varactor. Moreover, the 1×10^{-5} load-reactance stability must be maintained not only under benign conditions, but also under changing environmental conditions (temperature, vibration, radiation, etc.). Therefore, the wider the tuning range of an oscillator, the more difficult it is to maintain a high stability.

4. *Quartz and the Quartz Crystal Unit*

A quartz crystal unit's high Q and high stiffness (small C_1) make it the primary frequency- and frequency-stability-determining element in a crystal oscillator. The Q values of crystal units are much higher than those attainable with other circuit elements. In general purpose crystal units, Qs are generally in the range of 10^4 to 10^6. A high-stability 5-MHz crystal unit's Q is typically in the range of two to three million. The intrinsic Q, limited by internal losses in the crystal, has been determined experimentally to be inversely proportional to frequency (i.e., the Qf product is a constant for a given resonator type). For AT- and SC-cut resonators, the maximum $Qf = 16$ million when f is in MHz.

Quartz (which is a single-crystal form of SiO_2) has been the material of choice for stable resonators since shortly after piezoelectric crystals were first used in oscillators—in 1918. Although many other materials have been explored, none has been found to be better than quartz. Quartz is the only material known that possesses the following combination of properties:

1. It is piezoelectric ("pressure electric"; *piezein* means "to press" in Greek).
2. Zero temperature coefficient resonators can be made when the plates are cut along the proper directions with respect to the crystallographic axes of quartz.
3. Of the zero temperature coefficient cuts, one, the SC-cut (see below), is "stress compensated."
4. It has low intrinsic losses (i.e., quartz resonators can have high Qs).
5. It is easy to process because it is hard but not brittle, and, under normal conditions, it has low solubility in everything except the fluoride etchants.

6. It is abundant in nature.
7. It is easy to grow in large quantities, at low cost, and with relatively high purity and perfection.

The direct piezoelectric effect was discovered by the Curie brothers in 1880. They showed that when a weight was placed on a quartz crystal, charges appeared on the crystal surface; the magnitude of the charge was proportional to the weight. In 1881, the converse piezoelectric effect was illustrated; when a voltage was applied to the crystal, the crystal deformed due to the lattice strains caused by the effect. The strains reversed when the voltage was reversed.

Of the 32 crystal classes, 20 exhibit the piezoelectric effect (but only a few of these are useful). Piezoelectric crystals lack a center of symmetry. When a force deforms the lattice, the centers of gravity of the positive and negative charges in the crystal can be separated so as to produce surface charges. The piezoelectric effect can provide a coupling between an electrical circuit and the mechanical properties of a crystal. Under the proper conditions, a "good" piezoelectric resonator can stabilize the frequency of an oscillator circuit.

Quartz crystals are highly *anisotropic*, that is, the properties vary greatly with crystallographic direction. For example, when a quartz sphere is etched in hydrofluoric acid, the etching rate is more than 100 times faster along the fastest etching rate direction, the *Z* direction, than along the slowest direction, the slow-*X* direction. The constants of quartz, such as the thermal expansion coefficient and the temperature coefficients of the elastic constants, also vary with direction. That crystal units can have zero temperature coefficients of frequency is a consequence of the temperature coefficients of the elastic constants ranging from negative to positive values.

The locus of zero-temperature-coefficient cuts in quartz is shown in Fig. 7. The *X*, *Y*, and *Z* directions have been chosen to make the description of properties as simple as possible. The *Z*-axis in Fig. 5 is an axis of threefold symmetry in quartz; in other words, the physical properties repeat every 120° as the crystal is rotated about the *Z*-axis. The cuts usually have two-letter names, where the "T" in the name indicates a temperature-compensated cut; for instance, the AT-cut was the first temperature-compensated cut discovered. The FC-, IT-, BT-, and RT-cuts are other cuts along the zero-temperature-coefficient locus. These cuts were studied in the past (before the discovery of the SC-cut) for some special properties, but are rarely used today. The highest-stability crystal oscillators employ SC-cut or AT-cut crystal units.

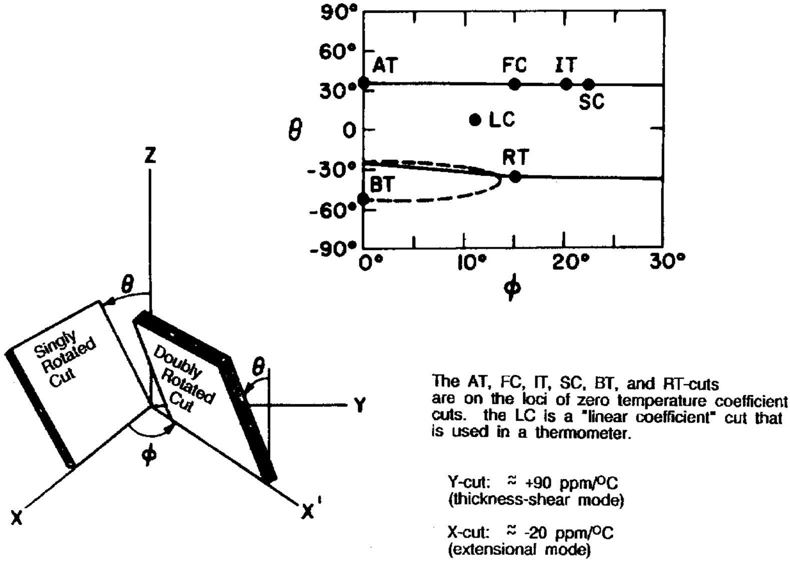


FIG. 7. Zero-temperature-coefficient cuts of quartz.

Because the properties of a quartz crystal unit depend strongly on the angles of cut of the crystal plate, in the manufacture of crystal units the plates are cut from a quartz bar along precisely controlled directions with respect to the crystallographic axes. The orientations of the plates are checked by means of x-ray diffraction. In some applications, the orientations must be controlled with accuracies of a few seconds of angle. After shaping to required dimensions, metal electrodes are applied to the wafer. Circular plates with circular electrodes are the most commonly used geometries, although the blanks and electrodes may also be of other geometries. The electroded wafer is mounted in a holder structure [38]. Figure 8 shows the two common types of holder structures used for resonators with frequencies greater than 1 MHz. (The 32-kHz tuning fork resonators used in quartz watches are packaged typically in small tubular enclosures.)

Because quartz is piezoelectric, a voltage applied to the electrodes causes the quartz plate to deform slightly. The amount of deformation due to an alternating voltage depends on how close the frequency of the applied voltage is to a natural mechanical resonance of the crystal. To describe the behavior of a resonator, the differential equations for Newton's laws of motion for a continuum, and for Maxwell's equations, must be solved with the proper

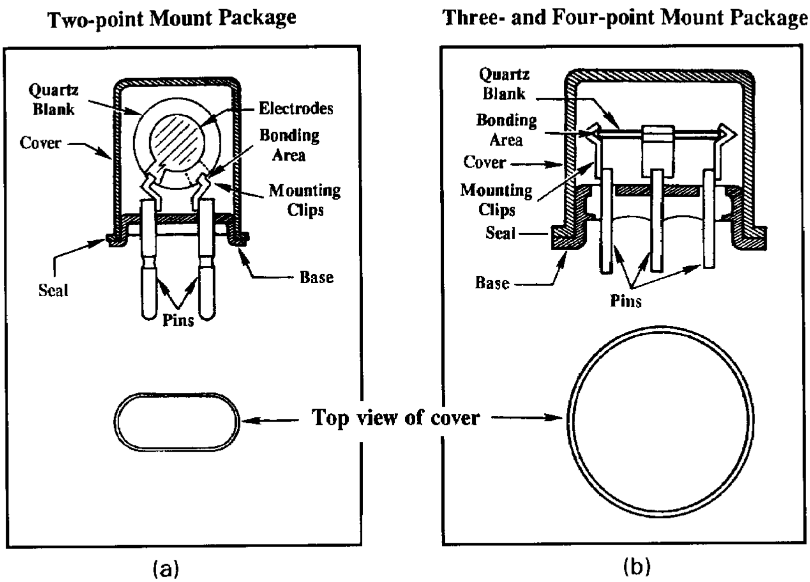


FIG. 8. Typical constructions of AT-cut and SC-cut crystal units: (a) two-point mount package; (b) three- and four-point mount package.

electrical and mechanical boundary conditions at the plate surfaces [39]. Because quartz is anisotropic and piezoelectric, with ten independent linear constants and numerous higher-order constants, the equations are complex and have never been solved in closed form for physically realizable three-dimensional resonators. Nearly all theoretical works have used approximations. The nonlinear elastic constants, although small, are the source of some of the important instabilities of crystal oscillators, such as the acceleration sensitivity, the thermal-transient effect, and the amplitude-frequency effect, each of which is discussed in this chapter.

In an ideal resonator, the amplitude of vibration is maximum at the center of the electrodes; it falls off exponentially outside the electrodes, as shown in the lower right portion of Fig. 9. In a properly designed resonator, a negligible amount of energy is lost to the mounting and bonding structure, i.e., the edges must be inactive for the resonator to be able to possess a high Q. The displacement of a point on the resonator surface is proportional to the drive current. At the typical drive currents used in (e.g., 10-MHz) thickness-shear resonators, the peak displacement is on the order of a few atomic spacings. (The peak acceleration of a point on the electrodes is on the order of 1 million g.)

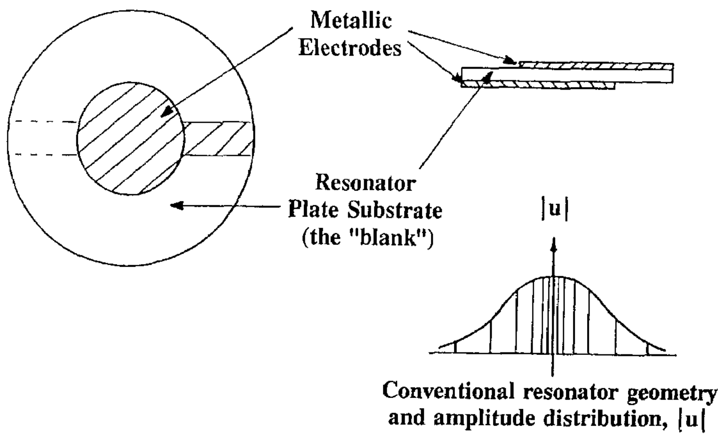


FIG. 9. Resonator vibration amplitude distribution for a circular plate with circular electrodes.

As the drive level (the current through a crystal) increases, the crystal's amplitude of vibration also increases, and the effects due to the nonlinearities of quartz become more pronounced. Some of the many properties that depend on the drive level are resonance frequency, motional resistance R_1, phase noise, frequency-vs-temperature anomalies (called *activity dips*), and frequency jumps, which are discussed in other sections of this chapter. The drive-level dependence of the resonance frequency, called the *amplitude-frequency effect*, is illustrated in Fig. 10 [40]. The frequency change with drive level is proportional to the square of the drive current; the coefficient depends on resonator design [41]. Because of the drive-level dependence of frequency, the highest-stability oscillators usually contain some form of automatic level control to minimize frequency changes due to oscillator circuitry changes. At high drive levels, the nonlinear effects also result in an increase in the resistance [35]. Crystals can also exhibit anomalously high starting resistance when the crystal surfaces possess such imperfections as scratches and particulate contamination. Under such conditions, the resistance at low drive levels can be high enough for an oscillator to be unable to start when power is applied. The drive-level dependence of resistance is illustrated in Fig. 11. In addition to the nonlinear effects, a high drive level can also cause a frequency change due to a temperature increase caused by the energy dissipation in the active area of the resonator.

Bulk acoustic wave (BAW) quartz resonators are available in the frequency range of about 1 kHz to 500 MHz. Surface acoustic wave (SAW) quartz

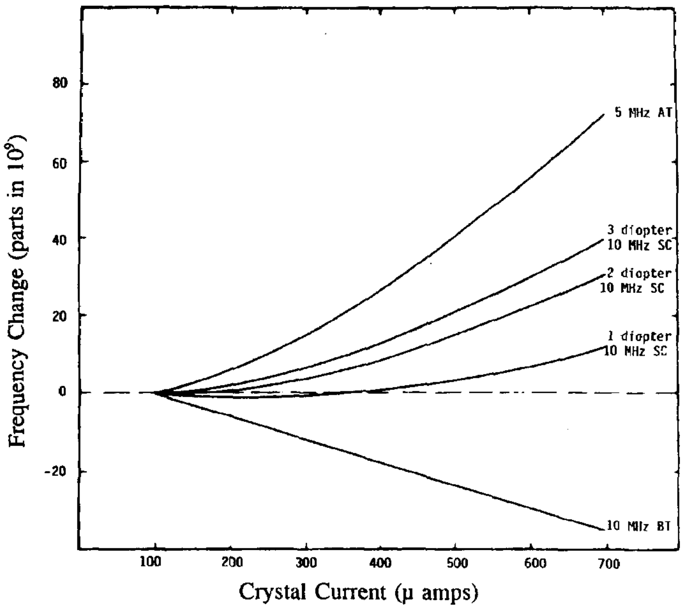


FIG. 10. Drive-level dependence of frequency.

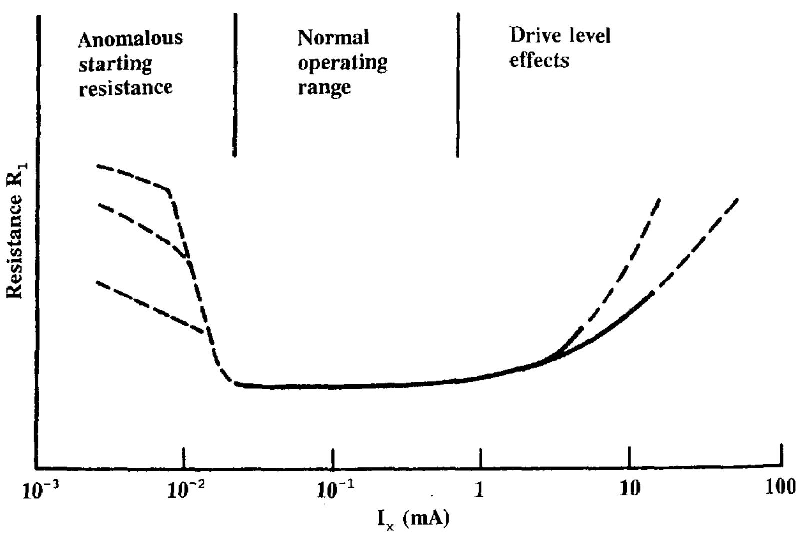


FIG. 11. Drive-level dependence of crystal unit resistance.

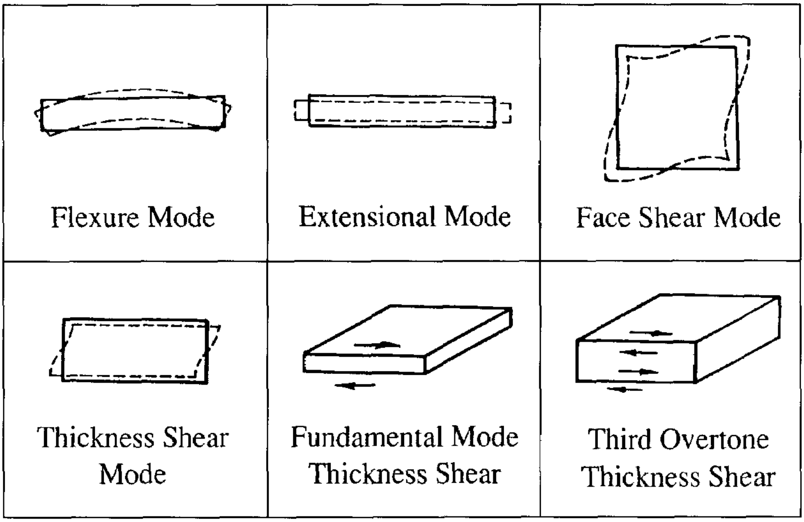


FIG. 12. Modes of motion of a quartz resonator.

resonators are available in the range of about 150 MHz to 1.5 GHz. To cover the wide range of frequencies, different cuts—vibrating in a variety of modes—are used. The bulk wave modes of motion are shown in Fig. 12. The AT-cut and SC-cut crystals vibrate in a thickness-shear mode. Although the desired thickness-shear mode usually exhibits the lowest resistance, the mode spectrum of even properly designed crystal units exhibits unwanted modes above the main mode. The unwanted modes, also called *spurious modes* or *spurs*, are especially troublesome in filter crystals, in which *energy-trapping rules* are employed to maximize the suppression of unwanted modes [34]. These rules specify certain electrode geometry to plate geometry relationships. In oscillator crystals, the unwanted modes may be suppressed sufficiently by providing a large enough plate diameter to electrode diameter ratio, or by contouring (i.e., generating a spherical curvature on one or both sides of the plate).

Above 1 MHz, the AT-cut is commonly used. For high-precision applications, the SC-cut has important advantages over the AT-cut. The AT-cut and SC-cut crystals can be manufactured for fundamental mode operation up to a frequency of about 300 MHz. (Higher than 1 GHz units have been produced on an experimental basis.) Above 100 MHz, overtone units that operate at a selected harmonic mode of vibration are generally used, although higher than 100 MHz fundamental mode units can be manufactured by means of chemical polishing (etching) techniques [42]. Below 1 MHz, tuning forks, *X*-*Y* and NT bars (flextural mode), +5° *X*-cuts (extensional mode), or CT-cut and DT-cut units (face shear mode) can be used. Tuning forks have become the dominant type of low-frequency units due to their small size and low cost.

A large number of tuning-fork crystals ($\sim 10^9$) are produced annually for the worldwide watch market and other applications. These tuning forks must be small, low cost, rugged, stable (as a function of temperature, time, and shock), and must allow a long battery life [43]. The requirements are met with tuning forks operating at 32,768 Hz (which is 2^{15} Hz). This frequency is a compromise among size, power requirement (i.e., battery life), stability, and manufacturing cost. In an analog watch, for example, the 32,768 Hz is divided by two 15 times, resulting in a 1 pulse per second output. These pulses drive a stepping motor that advances the second hand by 6° (i.e., 1/60th of a circle) once every second.

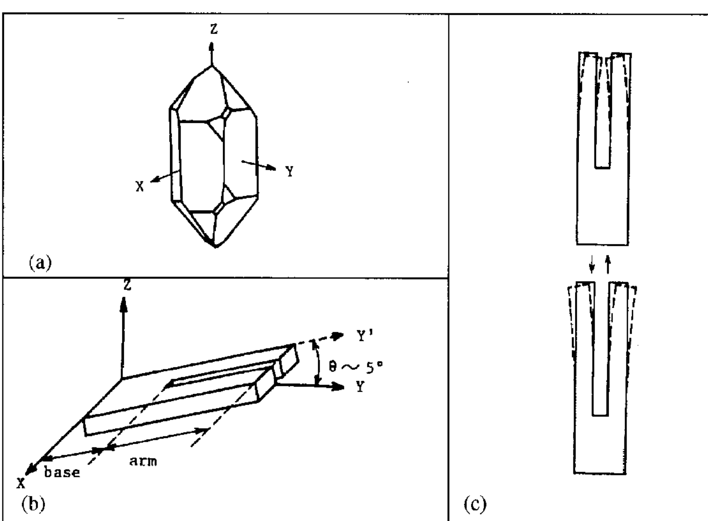


FIG. 13. (a) The natural faces and crystallographic axes of quartz; (b) orientation of the tuning fork with respect to the crystallographic axes; (c) flexural vibration mode of the tuning fork.

Figure 13(a) shows the natural faces and crystallographic axes of quartz, and Fig. 13(b) shows the orientation of the tuning fork with respect to these axes. After processing the tuning fork into a resonator, including the deposition of appropriate electrodes and hermetic sealing into an enclosure, and upon excitation with an appropriate oscillator circuit, the tuning fork vibrates in the flexural vibration mode shown in Fig. 13(c).

B. Oscillator Categories

A crystal unit's resonance frequency varies with temperature. Typical frequency vs temperature (f vs T) characteristics for crystals used in frequency standards are shown in Fig. 14. The three categories of crystal oscillators, based on the method of dealing with the crystal unit's f vs T characteristic, are XO, TCXO, and OCXO (see Fig. 15). A simple XO does not contain means for reducing the crystal's f vs T variation. A typical XO's f vs T stability may be ±25 ppm for a temperature range of −55 to +85°C.

In a TCXO, the temperature-dependent variations of a capacitor external to the crystal compensate for the crystal's f vs T characteristic [44]. The capacitance variations produce frequency changes that are equal and opposite to the frequency changes resulting from temperature changes; in other words,

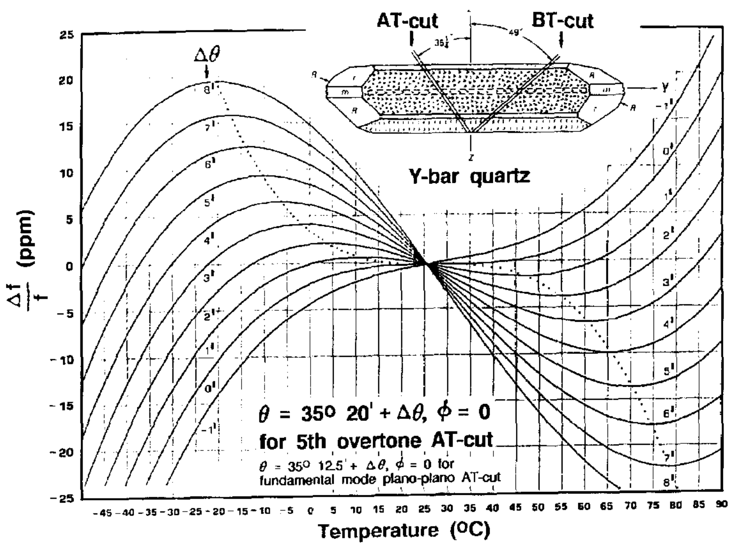


FIG. 14. Frequency versus temperature versus angle-of-cut characteristics of AT-cut crystals, with inset showing AT- and BT-but plates in *Y*-bar quartz.

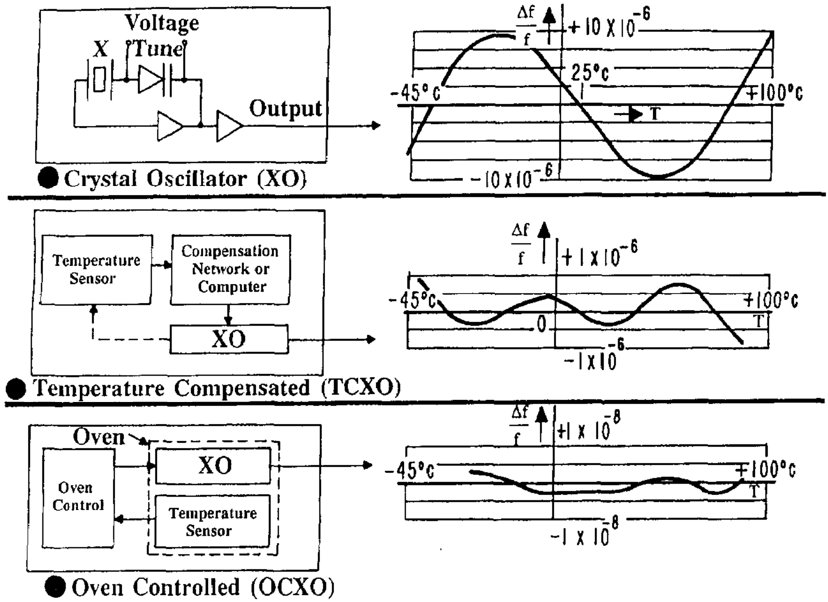


FIG. 15. Crystal oscillator categories based on the method of dealing with the crystal unit's frequency versus temperature characteristic.

the capacitance variations compensate for the crystal's f vs T variations. Analog TCXOs can provide about a twentyfold improvement over the crystal's f vs T variation. A good TCXO may have an f vs T stability of ± 1 ppm for a temperature range of -55 to $+85°C$.

In an OCXO, the crystal unit and other temperature-sensitive components of the oscillator circuit are maintained at a constant temperature in an oven [44]. The crystal is manufactured to have an f vs T characteristic that has zero slope at the oven temperature. To permit the maintenance of a stable oven temperature throughout the OCXO's temperature range (without an internal cooling means), the oven temperature is selected to be above the maximum operating temperature of the OCXO. OCXOs can provide more than a thousandfold improvement over the crystal's f vs T variation. A good OCXO may have an f vs T stability of better than $\pm 5 \times 10^{-9}$ for a temperature range of -55 to $+85°C$. OCXOs require more power, are larger, and cost more than TCXOs.

A special case of a compensated oscillator is the microcomputer-compensated crystal oscillator (MCXO) [45]. The MCXO overcomes the two major factors that limit the stabilities achievable with TCXOs: thermometry and the stability of the crystal unit. Instead of a thermometer that is external to the crystal unit, such as a thermistor, the MCXO uses a much more accurate "self-temperature sensing" method. Two modes of the crystal are excited simultaneously in a dual-mode oscillator. The two modes are combined such that the resulting beat frequency is a monotonic (and nearly linear) function of temperature. The crystal thereby senses its own temperature. To reduce the f vs T variations, the MCXO uses digital compensation techniques: pulse deletion in one implementation, and direct digital synthesis of a compensating frequency in another. The frequency of the crystal is not "pulled," which allows the use of high-stability (small C_1) SC-cut crystal units. A typical MCXO may have an f vs T stability of $\pm 2 \times 10^{-8}$ for a temperature range of -55 to $+85°C$.

C. Oscillator Circuit Types

Of the numerous oscillator circuit types, three of the more commonly discussed ones, the Pierce, the Colpitts, and the Clapp, consist of the same circuit except that the rf ground points are at different locations, as shown in Fig. 16. The Butler and modified Butler are also similar to each other; in each, the emitter current is the crystal current. The gate oscillator is a Pierce-type

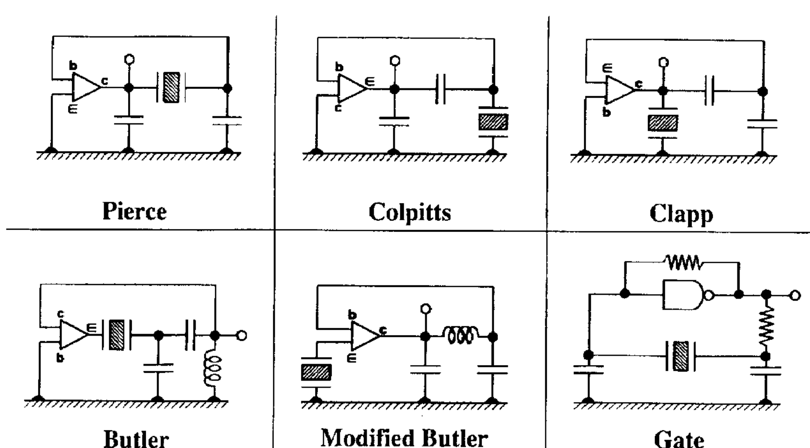


FIG. 16. Oscillator circuit types.

that uses a logic gate plus a resistor in place of the transistor in the Pierce oscillator. (Some gate oscillators use more than one gate.)

Information on designing crystal oscillators can be found in references 1, 2, 5, and 7. The choice of oscillator circuit type depends on such factors as the desired frequency stability, input voltage and power, output power and waveform, tunability, design complexity, cost, and the crystal unit's characteristics.

In the Pierce family, the ground point location has a profound effect on the performance. The Pierce configuration is generally superior to the others, e.g., with respect to the effects of stray reactances and biasing resistors, which appear mostly across the capacitors in the circuit rather than the crystal unit. It is one of the most widely used circuits for high-stability oscillators. In the Colpitts configuration, a larger part of the strays appears across the crystal, and the biasing resistors are also across the crystal, which can degrade performance. The Clapp is seldom used because, since the collector is tied directly to the crystal, it is difficult to apply a dc voltage to the collector without introducing losses or spurious oscillations. The Pierce family usually operates at parallel resonance (see Fig. 6), although it can be designed to operate at series resonance by connecting an inductor in series with the crystal. The Butler family usually operates at (or near) series resonance. The Pierce can be designed to operate with the crystal current above or below the emitter current. Gate oscillators are common in digital systems when high stability is not a major consideration. (See the references for more details on oscillator circuits.)

Most users require a sine wave, a TTL-compatible, a CMOS-compatible, or an ECL-compatible output. The latter three can be simply generated from a sine wave.

D. Oscillator Instabilities

1. Accuracy, Stability, and Precision

Oscillators exhibit a variety of instabilities. These include aging, noise, and frequency changes with temperature, acceleration, ionizing radiation, power supply voltage, etc. The terms *accuracy, stability,* and *precision* are often used in describing an oscillator's quality with respect to its instabilities. Figure 17 compares the meanings of these terms for a marksman and for a frequency source. (For the marksman, each bullet hole's distance to the center of the target is the "measurement.")

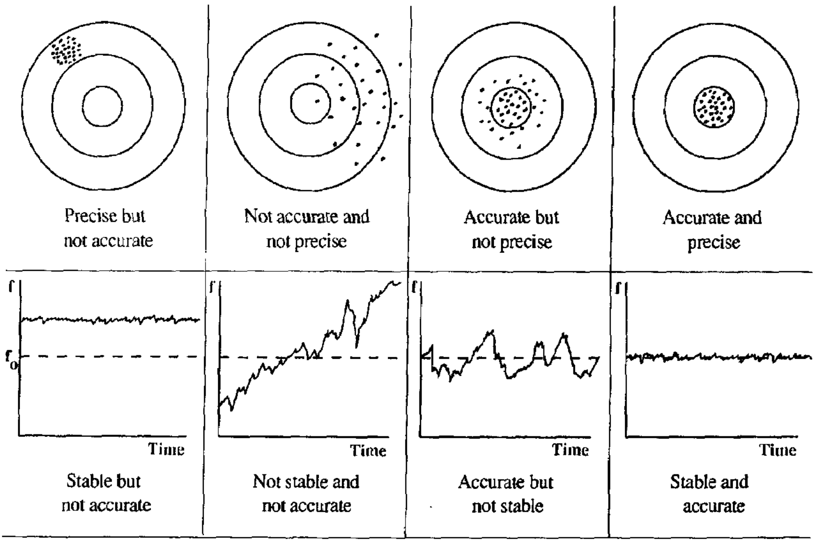


FIG. 17. Accuracy, stability, and precision examples for a marksman (top) and for a frequency source (bottom).

Accuracy is the extent to which a given measurement, or the average of a set of measurements for one sample, agrees with the definition of the quantity being measured. It is the degree of "correctness" of a quantity. Frequency standards have varying degrees of accuracy. The International System (SI) of units for time and frequency (second and Hz, respectively) are obtained in laboratories using very accurate atomic frequency standards called *primary* standards. A primary standard operates at a frequency calculable in terms of the SI definition of the second: "the duration of 9,192,2631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium atom 133" [46].

Reproducibility is the ability of a single frequency standard to produce the same frequency, without adjustment, each time it is put into operation. From the user's point of view, once a frequency standard is calibrated, reproducibility confers the same advantages as accuracy. *Stability* describes the amount something changes as a function of parameters such as time, temperature, shock, and the like. *Precision* is the extent to which a given set of measurements of one sample agrees with the mean of the set. (A related meaning of the term is used as a descriptor of the quality of an instrument, as in a "precision instrument." In that context, the meaning is usually defined as accurate and precise, although a precision instrument can also be inaccurate and precise, in which case the instrument needs to be calibrated.)

2. *Aging*

"Aging" and "drift" have occasionally been used interchangeably in the literature. However, recognizing the "need for common terminology for the unambiguous specification and description of frequency and time standard systems," the International Radio Consultative Committee (CCIR) adopted a glossary of terms and definitions in 1990 [47]. According to this glossary, *aging* is "the systematic change in frequency with time due to internal changes in the oscillator," and drift is "the systematic change in frequency with time of an oscillator." *Drift* due to aging plus changes in the environment and other factors external to the oscillator. Aging, not drift, is what one denotes in a specification document and what one measures during oscillator evaluation. Drift is what one observes in an application. For example, the drift of an oscillator in a spacecraft might be due to (the algebraic sum of) aging and frequency changes due to radiation, temperature changes in the spacecraft, and power supply changes.

Aging can be positive or negative [48]. Occasionally, a reversal in aging direction is observed. At a constant temperature, aging usually has an approximately logarithmic dependence on time. Typical (computer-simulated) aging behaviors are illustrated in Fig. 18, where $A(t)$ is a logarithmic function and $B(t)$ is the same function but with different coefficients. The curve showing the reversal is the sum of the other two curves. A reversal indicates the presence of at least two aging mechanisms. The aging rate of an oscillator is highest when it is first turned on. When the temperature of a crystal unit is changed (e.g., when an OCXO is turned off and turned on at a later time), a new aging cycle starts. (See the section concerning hysteresis and retrace below for additional discussion of the effects of temperature cycling.)

The primary causes of crystal oscillator aging are stress relief in the mounting structure of the crystal unit, mass transfer to or from the resonator's surfaces due to adsorption or desorption of contamination, changes in the oscillator circuitry, and, possibly, changes in the quartz material. Because the frequency of a thickness-shear crystal unit, such as an AT-cut or an SC-cut, is inversely proportional to the thickness of the crystal plate, and because a

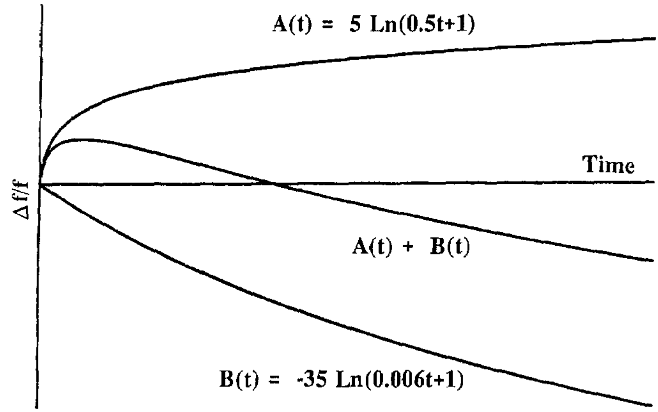


FIG. 18. Computer-simulated typical aging behaviors, where $A(t)$ and $B(t)$ are logarithm functions with different coefficients.

typical 5-MHz plate is on the order of 1 million atomic layers thick, the adsorption or desorption of contamination equivalent to the mass of one atomic layer of quartz changes the frequency by about 1 ppm. Therefore, to achieve low aging, crystal units must be fabricated and hermetically sealed in an ultraclean, ultra-high-vacuum environment. As of 1998, the aging rates of typical commercially available crystal oscillators range from 5 to 10 ppm per year for an inexpensive XO, to 0.5 to 2 ppm per year for a TCXO, and to 0.05 to 0.1 ppm per year for an OCXO. The highest precision OCXOs can age a few parts in 10^{12} per day, i.e., less than 0.01 ppm per year.

3. *Noise in Frequency Standards*

a. The Effects of Noise. Sometimes the suitability of oscillators for an application is limited by deterministic phenomena. In other instances, stochastic (random) processes establish the performance limitations. Except for vibration, the short-term instabilities almost always result from noise. Long-term performance of quartz and rubidium standards is limited primarily by the temperature sensitivity and the aging, but the long-term performance of cesium and some hydrogen standards is limited primarily by random processes.

Noise can have numerous adverse effects on system performance. Some of these effects are: (1) it limits the ability to determine the current state and the predictability of precision oscillators (e.g., the noise of an oscillator produces time prediction errors of $\sim\tau\sigma_y(\tau)$ for prediction intervals of τ); (2) it limits synchronization and syntonization accuracies; (3) it can limit a receiver's useful dynamic range, channel spacing, and selectivity; (4) it can cause bit errors in digital communications systems; (5) it can cause loss of lock, and limit acquisition and reacquisition capability in phase locked loop systems; and (6) it can limit radar performance, especially Doppler radar.

To characterize the random components of oscillator instability, appropriate statistical measures are necessary. Noise characterization has been reviewed [34, 49, 50] and is also the subject of an IEEE standard [51]. The two-sample deviation, denoted by $\sigma_y(\tau)$, is the measure of short-term instabilities in the time domain. The phase noise, denoted by $\mathscr{L}(f)$, is the measure of instabilities in the frequency domain. It is related to the phase instability, denoted by $S_\phi(f)$, by $\mathscr{L}(f) \equiv \frac{1}{2}S_\phi(f)$.

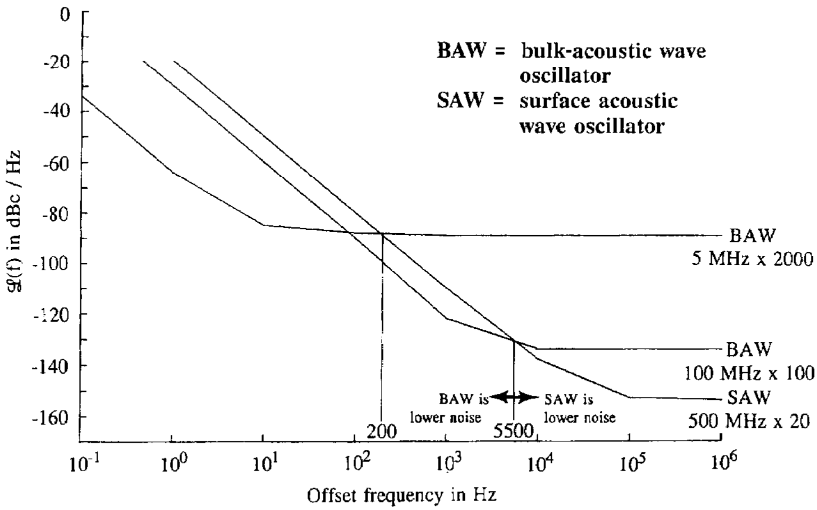
b. Noise in Crystal Oscillators. Although the causes of noise in crystal oscillators are not fully understood, several causes of short-term instabilities have been identified. Temperature fluctuations can cause short-term instabilities via thermal-transient effects (see Section III.D.4.b concerning dynamic f vs T effects), and via activity dips at the oven set point in OCXOs. Other causes include Johnson noise in the crystal unit, random vibration (see Section III.D.6 concerning acceleration effects in crystal oscillators), noise in the oscillator circuitry (both the active and passive components can be significant noise sources), and fluctuations at various interfaces on the resonator (e.g., in the number of molecules adsorbed on the resonator's surface).

In a properly designed oscillator, the resonator is the primary noise source close to the carrier and the oscillator circuitry is the primary source far from the carrier. The noise close to the carrier (i.e., within the bandwidth of the resonator) has a strong inverse relationship with resonator Q, such that $\mathscr{L}(f) \propto 1/Q^4$. In the time domain, $\sigma_y(\tau) \approx (2 \times 10^{-7})/Q$ at the noise floor. In the frequency domain, the noise floor is limited by Johnson noise, the noise power of which is $kT = -174$ dBm/Hz at 290 K. A higher signal (i.e., a higher resonator drive current) will improve the noise floor but not the close-in noise. In fact, for reasons that are not understood fully, above a certain point, higher drive levels usually degrade the close-in noise. For example, the maximum "safe" drive level is about 100 μa for a 5-MHz fifth overtone AT-cut resonator with $Q \approx 2.5$ million. The safe drive current can be substantially higher for high-frequency SC-cut resonators. For example, $\mathscr{L}(f) = -180\,\text{dBc/Hz}$ has been achieved with 100-MHz fifth overtone SC-cut resonators at drive currents $\approx 10\,\text{mA}$. However, such a noise capability is useful only in a vibration-free laboratory environment. If there is even a slight amount of vibration at the offset frequencies of interest, the vibration-induced noise will dominate the quiescent noise of the oscillator (see Section III.D.6).

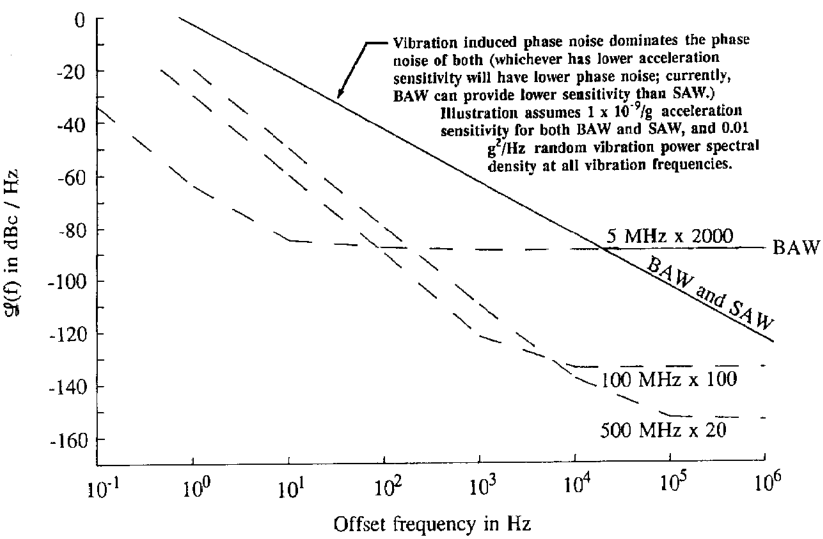
When low noise is required in the microwave (or higher) frequency range, SAW oscillators and dielectric resonator oscillators (DROs) are sometimes used. When compared with multiplied-up (bulk acoustic wave) quartz oscillators, these oscillators can provide lower noise far from the carrier at the expense of poorer noise close to the carrier, poorer aging, and poorer temperature stability. SAW oscillators and DROs can provide lower noise far from the carrier because these devices can be operated at higher drive levels, thereby providing higher signal-to-noise ratios, and because the devices operate at higher frequencies, thereby reducing the "20 log *N* losses" due to frequency multiplication by *N*. Noise floors at $\mathscr{L}(f) = -180\,\text{dBc/Hz}$ have been achieved with state-of-the-art SAW oscillators [50]. Of course, as is the case for high-frequency BAW oscillators, such noise floors are realizable only in environments that are free of vibrations at the offset frequencies of interest. Figures 19(a) and 19(b) show comparisons of state-of-the-art 5-MHz and 100-MHz BAW oscillators and a 500-MHz SAW oscillator, multiplied to 10 GHz. Figure 19(a) shows the comparison in a quiet environment, and Figure 19(b) shows it in a vibrating environment.

The short-term stability of TCXOs is temperature (*T*) dependent and is generally significantly worse than that of OCXOs, for the following reasons:

- The slope of the TCXO crystal's frequency (f) vs *T* varies with *T*. For example, the f vs *T* slope may be near zero at ~20°C, but it will be ~1 ppm/°C at the *T* extremes. *T* fluctuations will cause small f fluctuations at laboratory ambient *T*s, so the stability can be good there, but millidegree fluctuations will cause $\sim 10^{-9}$ f fluctuations at the *T* extremes. The TCXOs f vs *T* slopes also vary with *T*; the zeros and maxima can be at any *T*, and the maximum slopes can be on the order of 1 ppm/°C.
- AT-cut crystal's thermal transient sensitivity makes the effects of *T* fluctuations depend not only on the *T* but also on the rate of change



(a)



(b)

FIG. 19. (a) Low-noise SAW and BAW multiplied to 10 GHz (in a nonvibrating environment); (b) low-noise SAW and BAW multiplied to 10 GHz (in a vibrating environment).

of T (whereas the SC-cut crystals typically used in precision OCXOs are insensitive to thermal transients). Under changing T conditions, the T gradient between the T sensor (thermistor) and the crystal will aggravate the problems.

- TCXOs typically use fundamental mode AT-cut crystals, which have lower Q and larger C_1 than the crystals typically used in OCXOs. The lower Q makes the crystals inherently noisier, and the larger C_1 makes the oscillators more susceptible to circuitry noise.
- AT-cut crystals' f vs T often exhibit activity dips. At the Ts where the dips occur, the f vs T slope can be very high, so the noise due to T fluctuations will also be very high, e.g., $100\times$ degradation of $\sigma_y(\tau)$ and 30-dB degradation of phase noise are possible. Activity dips can occur at any T.

c. Frequency Jumps. When the frequencies of oscillators are observed for long periods, occasional frequency jumps can be observed. In precision oscillators, the magnitudes of the jumps are typically in the range of 10^{-11} to 10^{-9}. The jumps can be larger in general purpose units. The jumps occur many times a day in some oscillators, and much less than once a day in others. The frequency excursions can be positive or negative. The causes (and cures) are not well understood.

The causes are believed to include nearby spurious resonances, stress relief, changes in surface and electrode irregularities, and noisy active and passive circuit components. The effect can depend on resonator drive level; in some units, frequency jumps can be produced at certain drive levels (but not below or above). Aging affects the incidence. Well-aged units show a lower incidence of jumps than new units.

Environmental effects can also produce jumps. Magnetic field, pressure, temperature, and power transients can produce sudden frequency excursions, as can shock and vibration. It is not unusual, for example, to experience shock and vibration levels of >0.01 g in buildings as trucks pass by, heavy equipment is moved, boxes are dropped, etc. [$0.02\,\mathrm{g} \times 10^{-9}/\mathrm{g} = 2 \times 10^{-11}$].

4. Frequency versus Temperature Stability

a. Static Frequency versus Temperature Stability. As an illustration of the effects that temperature can have on frequency stability, Fig. 20 shows the effects of temperature on the accuracy of a typical quartz wristwatch. Near the wrist temperature, the watch can be very accurate because of the frequency of the crystal (i.e., the clock rate) changes very little with temperature. However,

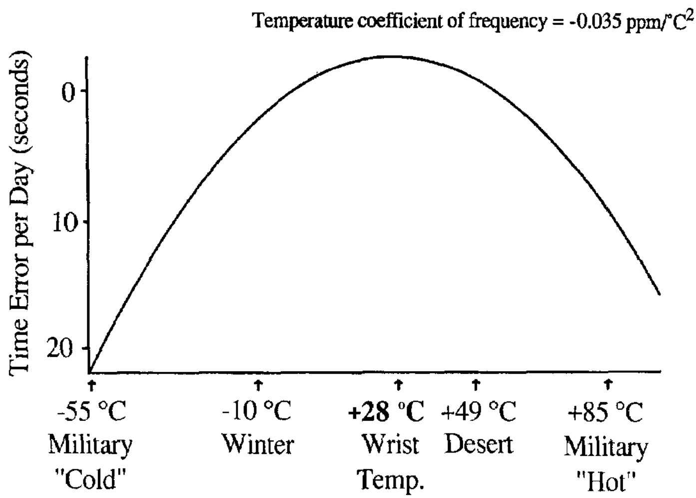


FIG. 20. Wristwatch accuracy as it is affected by temperature.

when the watch is cooled to −55°C or heated to +100°C, it loses about 20 seconds per day, because the typical temperature coefficient of frequency of the tuning-fork crystals used in quartz watches is −0.035 ppm/°C^2.

The static *f* vs *T* characteristics of crystal units are determined primarily by the angles of cut of the crystal plates with respect to the crystallographic axes of quartz [33–35]. "Static" means that the rate of change of temperature is slow enough for the effects of temperature gradients (explained later) to be negligible. As Fig. 14 illustrates for the AT-cut, a small change in the angle of cut can significantly change the *f* vs *T* characteristics. The points of zero temperature coefficient, the "turnover points," can be varied over a wide range by varying the angles of cut. The *f* vs *T* characteristics of SC-cut crystals are similar to the curves shown in Fig. 14, with the inflection temperature (T_i) shifted to about 95°C. (The exact value of T_i depends on the resonator's design.)

Other factors that can affect the *f* vs *T* characteristics of crystal units include the overtone [52]; the geometry of the crystal plate; the size, shape, thickness, density, and stresses of the electrodes; the drive level; impurities and strains in the quartz material; stresses in the mounting structure; interfering modes; ionizing radiation; the rate of change of temperature (i.e., thermal gradients) [53]; and thermal history. The last two factors are important for understanding the behaviors of OCXOs and TCXOs, and are, therefore, discussed separately.

The effect of harmonics, i.e. "overtones," on *f* vs *T* is illustrated for AT-cut crystals in Fig. 21 [52]. This effect is important for understanding the operation of the MCXO. The MCXO contains an SC-cut resonator and a dual-mode oscillator that excites both the fundamental mode and the third overtone of the resonator. The difference between the fundamental mode *f* vs *T* and the third overtone *f* vs *T* is due almost exclusively to the difference between the first-order temperature coefficients. Therefore, when the third overtone frequency is subtracted from three times the fundamental mode frequency, the resulting "beat frequency" is a monotonic and nearly linear function of temperature. This beat frequency enables the resonator to sense its own temperature.

Interfering modes can cause activity dips (see Fig. 22), which can cause oscillator failure [54]. Near the activity dip temperature, anomalies appear in both the *f* vs *T* and resistance (*R*) vs *T* characteristics. When the resistance increases at the activity dip, and the oscillator's gain margin is insufficient, the oscillator stops. Activity dips can be strongly influenced by the crystal's drive level and load reactance. The activity dip temperature is a function of C_L because the interfering mode usually has a large temperature coefficient and a C_1 that is different from that of the desired mode. Activity dips are troublesome in TCXOs, and also in OCXOs when the dip occurs at the oven temperature. The incidence of activity dips in SC-cut crystals is far lower than in AT-cut crystals.

An important factor that affects the *f* vs *T* characteristics of crystal oscillators is the load capacitor. When a capacitor is connected in series

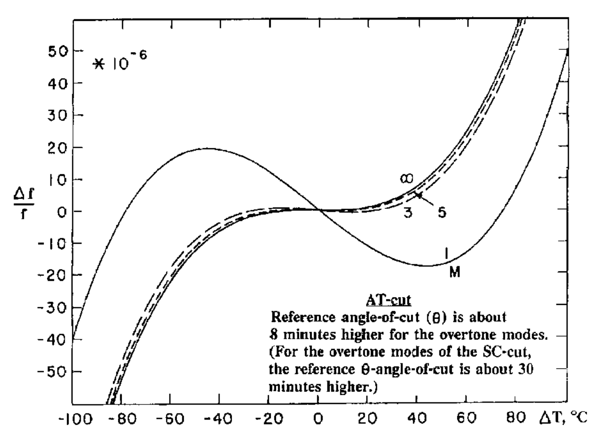


FIG. 21. Effects of harmonics on *f* vs *T*.

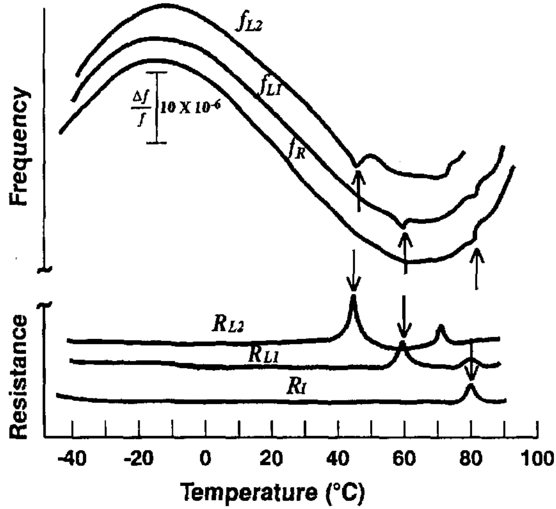


FIG. 22. Activity dips in the frequency versus temperature and resistance versus temperature characteristics, with and without C_L.

with the crystal, the f vs T characteristic of the combination is rotated slightly from that of the crystal alone. The temperature coefficient of the load capacitor can greatly magnify the rotation [55].

The f vs T of crystals can be described by a polynomial function. A cubic function is usually sufficient to describe the f vs T of AT-cut and SC-cut crystals to an accuracy of ± 1 ppm. In the MCXO, in order to fit the f vs T data to $\pm 1 \times 10^{-8}$, a polynomial of at least seventh order is usually necessary [56,57].

b. Dynamic Frequency versus Temperature Effects. Changing the temperature surrounding a crystal unit produces thermal gradients when, for example, heat flows to or from the active area of the resonator plate through the mounting clips. The static f vs T characteristic is modified by the thermal-transient effect resulting from the thermal-gradient-induced stresses [53]. When an OCXO is turned on, there can be a significant thermal-transient effect. Figure 23 shows what happens to the frequency output of two OCXOs, each containing an oven that reaches the equilibrium temperature in six minutes. One oven contains an AT-cut, the other, an SC-cut crystal. Thermal gradients in the AT-cut produce a large frequency undershoot that anneals out several minutes after the oven reaches equilibrium. The SC-cut crystal, being "stress-compensated" and thereby insensitive to such

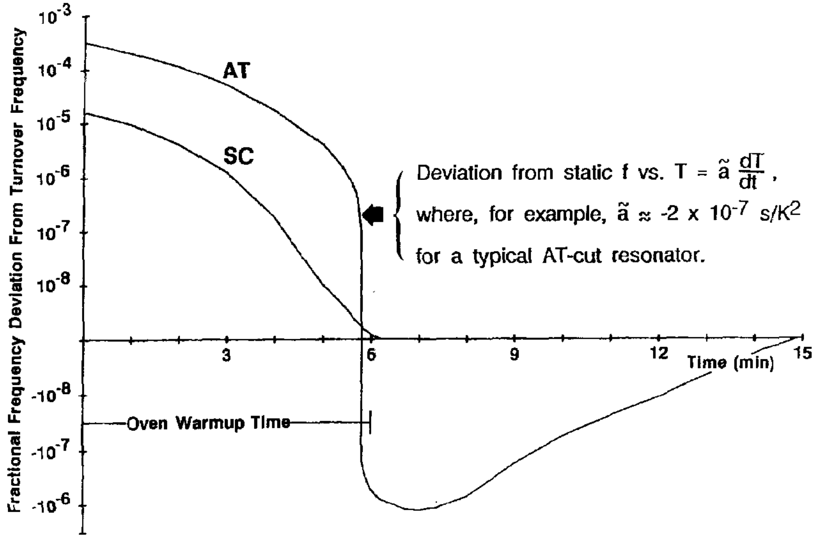


FIG. 23. Warm-up characteristics of AT-cut and SC-cut crystal oscillators (OCXOs).

thermal-transient-induced stresses, reaches the equilibrium frequency as soon as the oven stabilizes.

In addition to extending the warm-up time of OCXOs, when crystals other than SC-cuts are used, the thermal-transient effect makes it much more difficult to adjust the temperature of OCXO ovens to the desired turnover points, and the OCXO frequencies are much more sensitive to oven-temperature fluctuations [58].

The testing and compensation accuracies of TCXOs are also adversely affected by the thermal-transient effect. As the temperature is changed, the thermal-transient effect distorts the static f vs T characteristic, which leads to apparent hysteresis [57]. The faster the temperature is changed, the larger is the contribution of the thermal-transient effect to the f vs T performance.

c. Thermal Hysteresis and Retrace. The f vs T characteristics of crystal oscillators do not repeat exactly upon temperature cycling [58]. The lack of repeatability in TCXOs, "thermal hysteresis," is illustrated in Fig. 24. The lack of repeatability in OCXOs, "retrace," is illustrated in Fig. 25. *Hysteresis* is defined [59] as the difference between the up-cycle and the down-cycle f vs T characteristics and is quantified by the value of the difference at the temperature where the difference is maximum. Hysteresis is determined

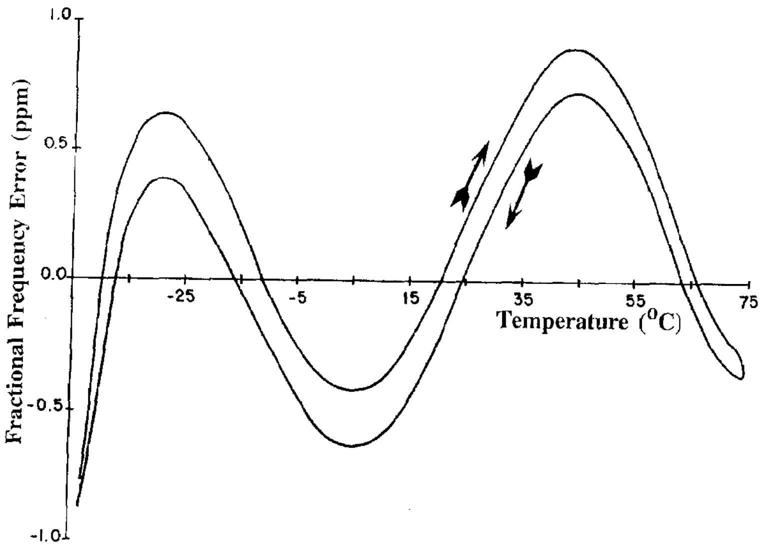


FIG. 24. Temperature-compensated crystal oscillator (TCXO) thermal hysteresis, showing that the first f vs T characteristic upon increasing temperature differs from the characteristic upon decreasing temperature.

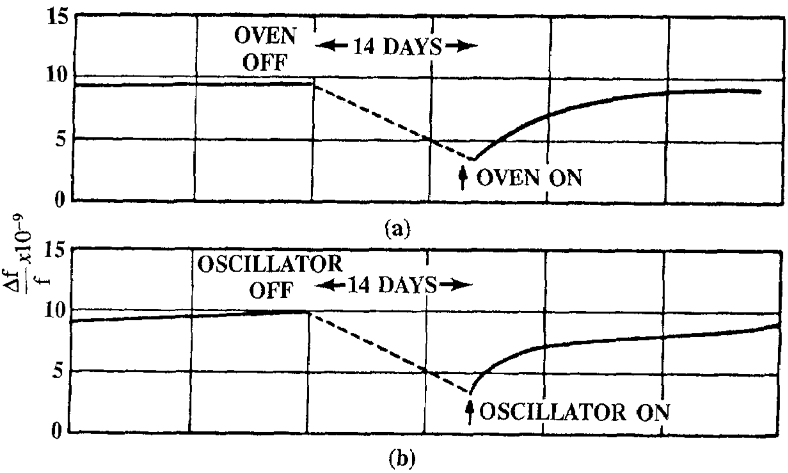


FIG. 25. Oven-controlled crystal oscillator (OCXO) retrace example, showing that upon restarting the oscillator after a 14-day off-period, the frequency was about 7×10^{-9} lower than what it was just before turn-off, and that the aging rate had increased significantly upon restart. About a month elapsed before the pre-turn-off aging rate was reached again. (The figure shows $\Delta f / f$ in parts in 10^{-9} vs time in days.)

during at least one complete quasi-static temperature cycle between specified temperature limits. *Retrace* is defined as the nonrepeatability of the f vs T characteristic at a fixed temperature (which is usually the oven temperature of an OCXO) upon on-off cycling an oscillator under specified conditions.

Hysteresis is the major factor limiting the stability achievable with TCXOs. It is especially so in the MCXO because, in principle, the digital compensation method used in the MCXO would be capable of compensating for the f vs T variations to arbitrary accuracy if the f vs T characteristics could be described by single-valued functions.

Retrace limits the accuracies achievable with OCXOs in applications where the OCXO is on-off cycled. Typical values of hysteresis in TCXOs range from 1 to 0.1 ppm when the temperature-cycling ranges are 0 to 60°C and −55 to +85°C. Hysteresis of less than 1×10^{-8} has been observed in SC-cut (MCXO) resonators [56]. The typical MCXO resonator hysteresis in early models of the MCXO was a few parts in 10^8 [56, 57]. Typical OCXO retrace specifications, after a 24-hour off period at about 25°C, range from 2×10^{-8} to 1×10^{-9}. Low-temperature storage during the off period, and extending the off period, usually make the retrace worse [58].

The causes of hysteresis and retrace are not well understood; the experimental evidence to date is inconclusive [58]. The mechanisms that can cause these effects include strain changes, changes in the quartz, oscillator circuitry changes, contamination redistribution in the crystal enclosure, and apparent hysteresis or retrace due to thermal gradients.

5. *Warm-Up*

When power is applied to a frequency standard, it takes a finite amount of time before the equilibrium frequency stability is reached. Figure 23, discussed above, illustrates the warm-up of two OCXOs. The warm-up time of an oscillator is a function of the thermal properties of the resonator, the oscillator circuit and oven construction, the input power, and the oscillator's temperature prior to turn-on. Typical warm-up time specifications of OCXOs (e.g., from a 0°C start) range from 3 to 10 minutes. Even TCXOs, MCXOs, and simple XOs take a few seconds to "warm up," although these are not ovenized. The reasons for the finite warm-up (i.e., stabilization) periods are that it takes a finite amount of time for the signal to build up in any high-Q circuit and that the few tens of milliwatts of power dissipated in these oscillators can change the thermal conditions within the oscillators.

6. Acceleration Effects

Acceleration changes a crystal oscillator's frequency [5, 6]. The acceleration can be a steady-state acceleration, vibration, shock, attitude change (2-g tipover), or acoustic noise. The amount of frequency change depends on the magnitude and direction of the acceleration $\vec{A}$, and on the acceleration sensitivity of the oscillator $\vec{\Gamma}$. The acceleration sensitivity is a vector quantity. The frequency change can be expressed as

$$\frac{\Delta f}{f} = \vec{\Gamma} \cdot \vec{A}$$

Typical values of $|\vec{\Gamma}|$ are in the range of 10^{-9}/g to 10^{-10}/g. For example, when $\vec{\Gamma} = 2 \times 10^{-9}$/g and is normal to the earth's surface, and the oscillator is turned upside down (a change of 2 g), the frequency changes by 4×10^{-9}. When this oscillator is vibrated in the up-and-down direction, the time-dependent acceleration modulates the oscillator's output frequency at the vibration frequency, with an amplitude of 2×10^{-9}/g.

When an oscillator is rotated 180° about a horizontal axis, the scalar product of the gravitational field and the unit vector normal to the initial "top" of the oscillator changes from −1 to +1 g, i.e., by 2 g. Figure 26 shows actual data of the fractional frequency shifts of an oscillator when the oscillator was rotated about three mutually perpendicular axes in the earth's gravitational field. For each curve, the axis of rotation was horizontal. The

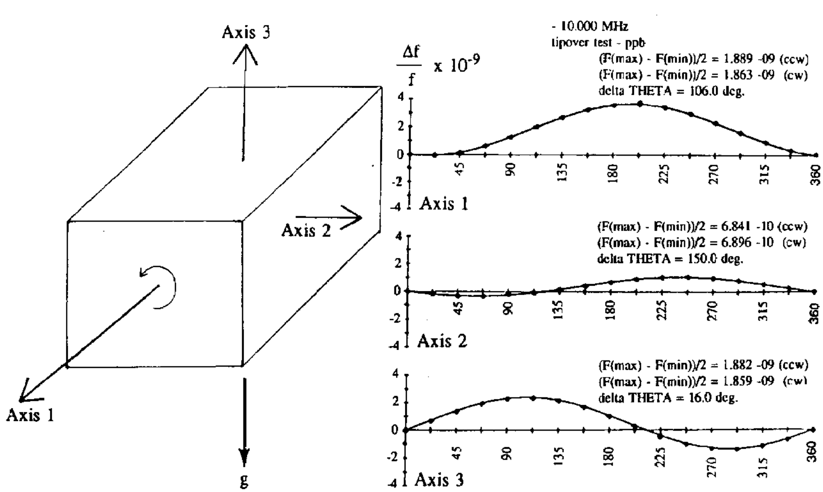


FIG. 26. 2-g tipover test (Δf vs attitude about three axes).

sinusoidal shape of each curve is a consequence of the scalar product being proportional to the cosine of the angle between the acceleration-sensitivity vector and the acceleration due to gravity [6].

In the frequency domain, the modulation results in vibration-induced sidebands that appear at plus and minus integer multiples of the vibration frequency from the carrier frequency. Figure 27 shows the output of a spectrum analyzer for a 10-MHz, 1.4×10^{-9}/g oscillator that was vibrated at 100 Hz and 10 g. For sinusoidal vibration, the "sidebands" are spectral lines. When the frequency is multiplied, as it is in many applications, the sideband levels increase by 20 dB for each 10 × multiplication. The increased sideband power is extracted from the carrier. Under certain conditions of multiplication, the carrier disappears, i.e., all the energy is then in the sidebands.

The acceleration sensitivity can be calculated from the vibration-induced sidebands. The preferred method is to measure the sensitivity at a number of vibration frequencies to reveal resonances. Figure 28 shows an example of the consequence of a resonance in an OCXO. In this case, the resonance was at 424 Hz, and it amplified the acceleration sensitivity seventeenfold.

The effect of random vibration is to raise the phase noise level of the oscillator. The degradation of phase noise can be substantial when the oscillator is on a vibrating platform, such as on an aircraft. Figure 2

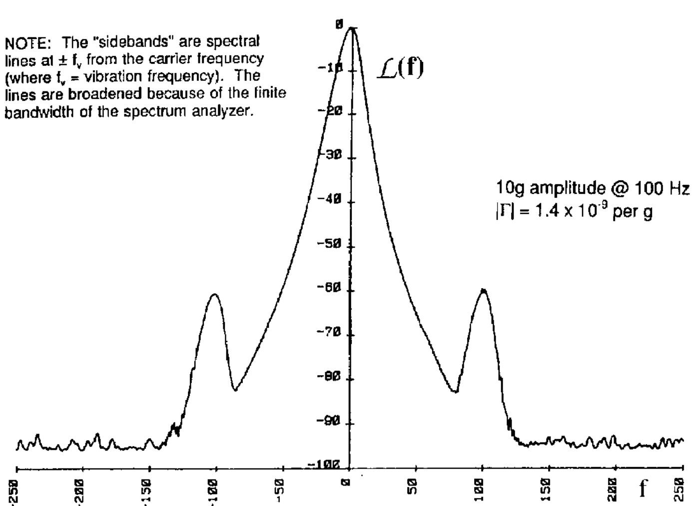


FIG. 27. Vibration-induced "sidebands" (i.e., spectral lines).

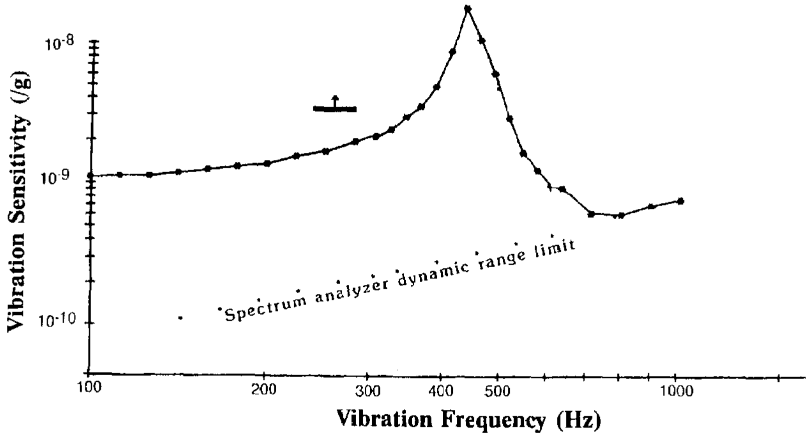


FIG. 28. Resonance in the acceleration sensitivity vs vibration frequency characteristic.

showed a typical aircraft random-vibration specification (power spectral density [PSD] vs vibration frequency) and the resulting vibration-induced phase noise degradation. Acoustic noise is another source of acceleration that can affect the frequency stability of oscillators.

The peak phase excursion, ϕ_{peak}, due to sinusoidal vibration is

$$\phi_{\text{peak}} = \frac{\Delta f}{f_v} = \frac{\vec{\Gamma} \cdot \vec{A} f_0}{f_v} \text{ radians.}$$

Upon frequency multiplication, ϕ_{peak} increases by the multiplication factor. For example, if $\vec{\Gamma} \cdot \vec{A} = 1 \times 10^{-9}$, $f_0 = 10$ MHz, and $f_v = 10$ Hz, then $\phi_{\text{peak}} = 1 \times 10^{-3}$ rad. If this oscillator's frequency is multiplied to 10 GHz (e.g., in a radar system), then at 10 GHz, $\phi_{\text{peak}} = 1$ rad. Such large phase excursions can be catastrophic to many systems.

Figure 29 shows how the probability of detection for a coherent radar system varies with the phase noise of the reference oscillator [60]. The phase noise requirement for a 90% probability of detection of a 4 km/hr target is −130 dBc per Hz at 70 Hz from the carrier, for a 10-MHz oscillator. Such as phase noise is well within the capability of 10-MHz oscillators, provided that the oscillators are in a quiet environment. However, when the oscillators are on a vibrating platform, such as an airborne radar system, the phase noise of even the best available oscillators (as of 1997) is degraded by an amount that reduces the probability of detection to zero.

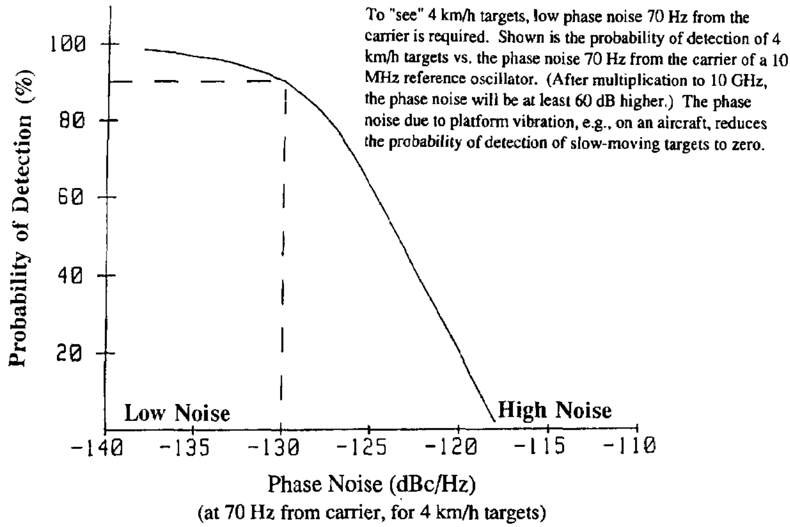


FIG. 29. Coherent radar probability of detection as a function of reference oscillator phase noise.

During shock, a crystal oscillator's frequency changes suddenly due to the sudden acceleration, as is illustrated in Fig. 30. The frequency change follows the expression above for acceleration-induced frequency change except if during the shock some elastic limits in the crystal's support structure or electrodes are exceeded (as is almost always the case during typical shock tests), the shock will produce a permanent frequency change.

Permanent frequency offsets due to shock can also be caused by change in the oscillator circuitry (e.g., due to movement of a wire or circuit board), and the removal of (particulate) contamination from the resonator surfaces. Resonances in the mounting structure will amplify the shock-induced stress.

If the shock level is sufficiently high, the crystal will break; however, in applications where high shock levels are a possibility, crystal units with chemically polished crystal plates can be used. Such crystals can survive shocks in excess of 30,000 g and have been fired successfully from howitzers [28, 29].

7. *Magnetic-Field Effects*

Quartz is diamagnetic; however, magnetic fields can affect magnetic materials in the crystal unit's mounting structure, electrodes, and enclosure. Time-

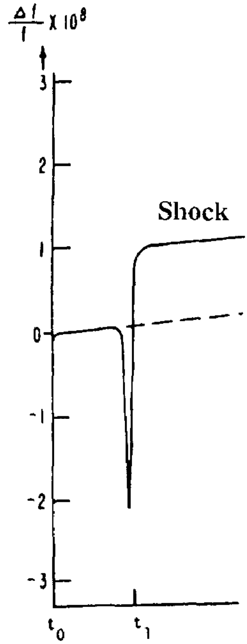


FIG. 30. The effect of a shock at $t = t_1$ on oscillator frequency.

varying electric fields will induce eddy currents in the metallic parts. Magnetic fields can also affect components such as inductors in the oscillator circuitry. When a crystal oscillator is designed to minimize the effects of magnetic fields, the sensitivity can be much less than 10^{-10} per oersted. Magnetic-field sensitivities on the order of 10^{-12} per oersted have been measured in crystal units designed specifically for low magnetic-field sensitivity [61].

8. *Radiation Effects*

Ionizing radiation changes a crystal oscillator's frequency primarily because of changes the radiation produces in the crystal unit [62, 63]. Under certain conditions, the radiation will also produce an increase in the crystal unit's equivalent series resistance. The resistance increase can be large enough to stop the oscillation when the oscillator is not radiation hardened.

Figure 31 shows a crystal oscillator's idealized frequency response to a pulse of ionizing radiation. The response consists of two parts. Initially, there is a transient frequency change that is due primarily to the thermal-transient effect caused by the sudden deposition of energy into the crystal unit. This

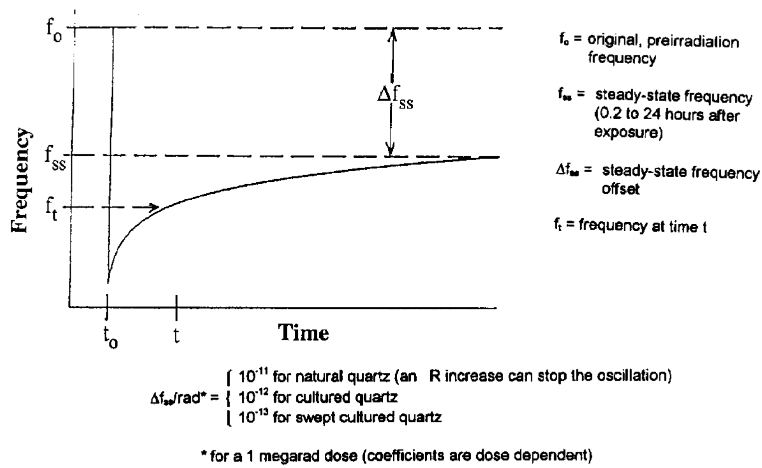


FIG. 31. Crystal oscillator's response to a pulse of ionizing radiation: f_o = original preirradiation frequency, Δf_{ss} = steady-state frequency offset (0.2 to 24 hours after exposure), f_t = instantaneous frequency at time t.

effect is a manifestation of the dynamic f vs T effect previously discussed. The transient effect is absent in SC-cut resonators made of high-purity quartz.

In the second part of the response, after steady state is reached, there is a permanent frequency offset that is a function of the radiation dose and the nature of the crystal unit. The frequency change versus dose is nonlinear, the change per rad being much larger at low doses than at large doses. At doses above 1 kilorad (SiO_2), the rate of frequency change with dose is quartz-impurity-defect dependent. For example, at a 1-megarad dose, the frequency change can be as large as 10 ppm when the crystal unit is made from natural quartz; it is typically 1 to a few ppm when the crystal is made from cultured quartz, and it can be as small as 0.02 ppm when the crystal is made from swept cultured quartz.

The impurity defect of major concern in quartz is the substitutional Al^{3+} defect with its associated interstitial charge compensator, which can be an H^+, Li^+, or Na^+ ion, or a hole. This defect substitutes for a Si^{4+} in the quartz lattice. Radiation can result in a change in the position of weakly bound compensators, which changes the elastic constants of quartz and thereby leads to a frequency change. The movement of ions also results in a decrease in the crystal's Q, i.e., in an increase in the crystal's equivalent series resistance, especially upon exposure to a pulse of ionizing radiation. If the oscillator's gain margin is insufficient, the increased resistance can stop the oscillation for periods lasting many seconds. A high-level pulse of ionizing radiation will produce photocurrents in the circuit, which result in a momentary cessation of oscillation, independent of the type of quartz used in the resonator. In oscillators using properly designed oscillator circuitry and resonators made of swept quartz, the oscillator recovers within 15 μs after exposure [64, 65].

Sweeping is a high-temperature, electric-field-driven, solid-state purification process in which the weakly bound alkali compensators are diffused out of the lattice and replaced by more tightly bound H^+ ions and holes [66, 67]. In the typical sweeping process, conductive electrodes are applied to the Z surfaces of a quartz bar, the bar is heated to about 500°C, and a voltage is applied so as to produce an electric field of about 1 kilovolt per centimeter along the Z direction. After the current through the bar decays (due to the diffusion of impurities) to some constant value, the bar is cooled slowly, the voltage is removed, and then the electrodes are removed. Crystal units made from swept quartz exhibit neither the radiation-induced Q degradation nor the large radiation-induced frequency shifts. Swept quartz (or low-aluminum-content quartz) should be used in oscillators that are expected to be exposed to ionizing radiation.

At low doses (e.g., at a few rads), the frequency change per rad can be as high as 10^{-9} per rad [68]. The low-dose effect is not well understood. It is not impurity dependent, and it saturates at about 300 rads. At very high doses (i.e., at $\gg$1 Mrad), the impurity-dependent frequency shifts also saturate because, since the number of defects in the crystal are finite, the effects of the radiation interacting with the defects are also finite.

When a fast neutron hurtles into a crystal lattice and collides with an atom, the low dose effect is scattered like a billiard ball. A single such neutron can produce numerous vacancies, interstitials, and broken interatomic bonds. The effect of this "displacement damage" on oscillator frequency is dependent primarily on the neutron fluence. The frequency of oscillator increases nearly linearly with neutron fluence at rates of: 8×10^{-21} neutrons per square centimeter (n/cm^2) at a fluence range of 10^{10} to 10^{12} n/cm^2, 5×10^{-21}/n/cm^2 at 10^{12} to 10^{13} n/cm^2, and 0.7×10^{-21}/n/cm^2 at 10^{17} to 10^{18} n/cm^2.

9. *Other Effects on Stability*

Ambient pressure change (as during an altitude change) can change a crystal oscillator's frequency if the pressure change produces a deformation of the crystal unit's or the oscillator's enclosure (thus changing stray capacitances and stresses). The pressure change can also affect the frequency indirectly through a change in heat-transfer conditions inside the oscillator. Humidity changes can also affect the heat-transfer conditions. In addition, moisture in the atmosphere will condense on surfaces when the temperature falls below the dew point, and can permeate materials such as epoxies and polyimides, and thereby affect the properties (e.g., conductivities and dielectric constants) of the oscillator circuitry. The frequency of a properly designed crystal oscillator changes less than 5×10^{-9} when the environment changes from one atmosphere of air to a vacuum. The medium- and long-term stability of some oscillators can be improved by controlling the pressure and humidity around the oscillators [69, 70].

Electric fields can change the frequency of a crystal unit. An ideal AT-cut is not affected by a dc voltage on the crystal electrodes, but "doubly rotated cuts," such as the SC-cut, are affected. For example, the frequency of a 5-MHz fundamental mode SC-cut crystal changes 7×10^{-9} per volt. Direct-current voltages on the electrodes can also cause sweeping, which can affect the frequencies of all cuts.

Power-supply and load-impedance changes affect the oscillator circuitry and, indirectly, the crystal's drive level and load reactance. A change in load impedance changes the amplitude or phase of the signal reflected into the oscillator loop, which changes the phase (and frequency) of the oscillation [70]. The effects can be minimized through voltage regulation and the use of buffer amplifiers. The frequency of a "good" crystal oscillator changes less than 5×10^{-10} for a 10% change in load impedance. The typical sensitivity of a high-quality crystal oscillator to power-supply voltage changes in 5×10^{-11} *N*.

Gas permeation under conditions where there is an abnormally high concentration of hydrogen or helium in the atmosphere can lead to anomalous aging rates. For example, hydrogen can permeate into "hermetically" sealed crystal units in metal enclosures, and helium can permeate through the walls of glass-enclosed crystal units.

10. Interactions among the Influences on Stability

The various influences on frequency stability can interact in ways that lead to erroneous test results if the interfering influence is not recognized during testing. For example, building vibrations can interfere with the measurement of short-term stability. Vibration levels of 10^{-3} to 10^{-2} g are commonly present in buildings. Therefore, if an oscillator's acceleration sensitivity is 1×10^{-9}/g, then the building vibrations alone can contribute short-term instabilities at the 10^{-12} to 10^{-11} level.

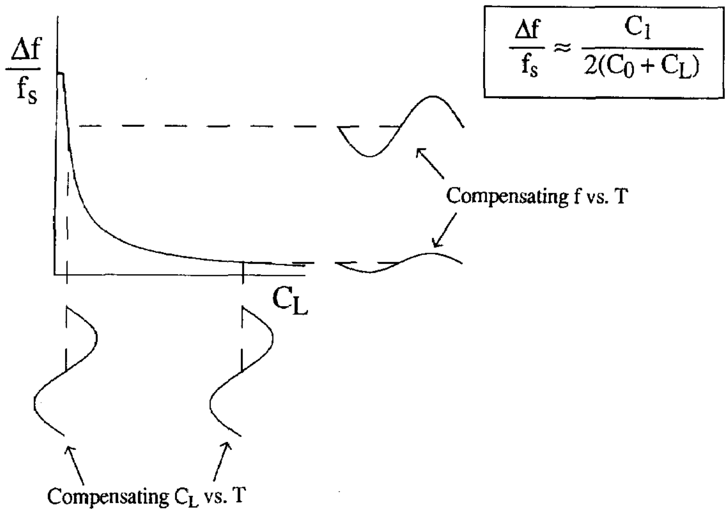
The 2-g tipover test is often used to measure the acceleration sensitivity of crystal oscillators. Thermal effects can interfere with this test because, when an oscillator is turned upside down, the thermal gradients inside the oven can vary due to changes in convection currents [6]. Other examples of interfering influences include temperature and drive-level changes interfering with aging tests; induced voltages due to magnetic fields interfering with vibration-sensitivity tests; and the thermal-transient effect, humidity changes, and the effect of the load-reactance temperature coefficient interfering with the measurement of crystal units' static f vs T characteristics.

An important effect in TCXOs is the interaction between the frequency adjustment during calibration and the f vs T stability [71]. This phenomenon is called the *trim effect*. In TCXOs, a temperature-dependent signal from a thermistor is used to generate a correction voltage that is applied to a varactor in the crystal network. The resulting reactance variations compensate for the crystal's f vs T variations. During calibration, the crystal's load reactance is varied to compensate for the TCXO's aging. Since the frequency vs reactance relationship is nonlinear, the capacitance change during calibration moves the operating point on the frequency vs reactance curve to a point where the slope of the curve is different, which changes the compensation (i.e., compensating for aging degrades the f vs T stability). Figure 32(a) shows how, for the same compensating C_L vs T, the compensating f vs T changes when the operating point is moved to a different C_L. Figure 32(b) shows test results for a 0.5-ppm TCXO that had a ± 6 ppm frequency-adjustment range (to allow for aging compensation for the life of the device). When delivered, this TCXO met its 0.5 ppm f vs T specification; however, when the frequency was adjusted ± 6 ppm during testing, the f vs T performance degraded significantly.

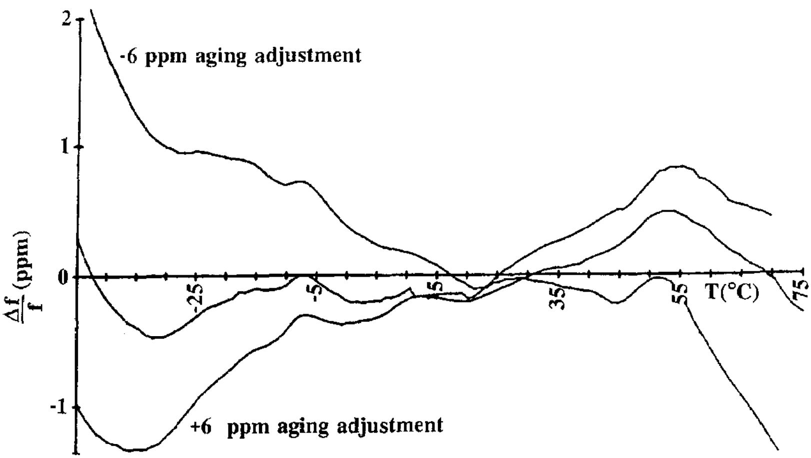
E. Oscillator Comparison and Selection

The discussion that follows applies to wide-temperature-range frequency standards (i.e., to those designed to operate over a temperature range that spans at least 90°C). Laboratory devices that operate over a much narrower temperature range can have much better stabilities than those in the comparison that follows.

Commercially available frequency sources cover an accuracy range of several orders of magnitude—from the simple XO to the cesium-beam frequency standard. As the accuracy increases, so does the power requirement, size, and cost. Figure 33, for example, shows the relationship between accuracy and power requirement. Accuracy versus cost would be a similar



(a)



(b)

FIG. 32. (a) Change in compensating frequency vs temperature due to C_L change; (b) temperature-compensated crystal oscillator (TCXO) trim effect.

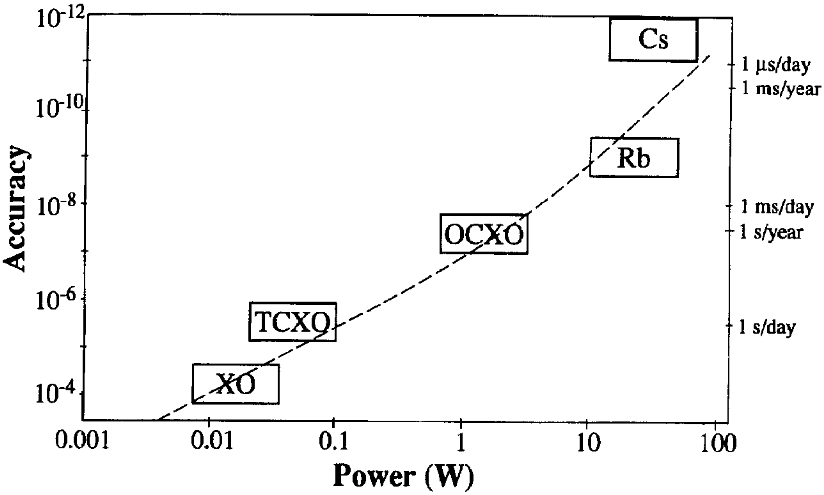


FIG. 33. Relationship between accuracy and power requirements (XO: simple crystal oscillator, TCXO: temperature-compensated crystal oscillator, OCXO: oven-controlled crystal oscillator, RB: rubidium frequency standard, CS: cesium beam frequency standard).

relationship, ranging from about $1 for a simple XO to about $50,000 for a cesium standard (1997 prices). Table 2 shows a comparison of salient characteristics of frequency standards.

Characteristics are provide in Table 2 for atomic oscillators: rubidium and cesium frequency standards and the rubidium-crystal oscillator (RbXO). In atomic frequency standards, the output signal frequency is determined by the energy difference between two atomic states rather than by some property of a bulk material (as it is in quartz oscillators). An introductory review of atomic frequency standards can be found in reference 74, and reference 34 is a review of the literature up to 1983. (Reference 74 reviews both atomic and quartz frequency standards; parts of this chapter are based on the quartz portion of that document.) The RbXO is a device intended for applications where power availability is limited, but where atomic frequency standard accuracy is needed [72, 73]. It consists of a rubidium frequency standard, a low-power, high-stability crystal oscillator, and control circuitry that adjusts the crystal oscillator's frequency to that of the rubidium standard. The rubidium standard is turned on periodically (e.g., once a week) for the few minutes it takes for it to warm up and correct the frequency of the crystal oscillator. With the RbXO, one an approach the long-term stability of the rubidium standard with the low (average) power requirement of the crystal oscillator.

TABLE 2

Comparison of Frequency Standards' Salient Characteristics

	Quartz Oscillators			Atomic Oscillators		
	TCXO	MCXO	OCXO	Rubidium	RbXO	Cesium
Accuracy* (per year)	2×10^{-6}	5×10^{-8}	1×10^{-8}	5×10^{-10}	7×10^{-10}	2×10^{-11}
Aging/Year	5×10^{-7}	2×10^{-8}	5×10^{-9}	2×10^{-10}	2×10^{-10}	0
Temp. Stab. (range, °C)	5×10^{-7} (−55 to +85)	3×10^{-8} (−55 to +85)	1×10^{-9} (−55 to +85)	3×10^{-10} (−55 to +68)	5×10^{-10} (−55 to +85)	2×10^{-11} (−28 to +65)
Stability, $\sigma_y(\tau)$ ($\tau = 1$ s)	1×10^{-9}	3×10^{-10}	1×10^{-12}	3×10^{-12}	5×10^{-12}	5×10^{-11}
Size (cm^3)	10	30	20–200	300–800	1000	6000
Warm-Up Time (min)	0.1 (to 1×10^{-6})	0.1 (to 2×10^{-8})	4 (to 1×10^{-8})	3 (to 5×10^{-10})	3 (to 5×10^{-10})	20 (to 2×10^{-11})
Power (W) (at lowest temp.)	0.04	0.04	0.6	20	0.65	30
Price (~$)	10–100	<1000	200–2000	2000–8000	<10,000	40,000

* Including environmental effects (note that the temperature ranges for rubidium and cesium are narrower than for quartz).

The major questions to be answered in choosing an oscillator include:

1. What frequency accuracy or reproducibility is needed for the system to operate properly?
2. How long must this accuracy be maintained, i.e., will the oscillator be calibrated or replaced periodically, or must the oscillator maintain the required accuracy for the life of the system?
3. Is ample power available, or must the oscillator operate from batteries?
4. What warm-up time, if any, is permissible?
5. What are the environmental extremes in which the oscillator must operate?
6. What is the short-term stability (phase noise) requirement?
7. What is the size constraint?

In relation to the second question, what cost is to be minimized: the initial acquisition cost or the life-cycle cost? Often, the cost of recalibration is far higher than the added cost of an oscillator that can provide calibration-free life. A better oscillator may also allow simplification of the system's design.

The frequency of the oscillator is another important consideration, because the choice can have a significant impact on both the cost and the performance. Everything else being equal, an oscillator of standard frequency, such as 5 or 10 MHz, for which manufacturers have well-established designs, will cost less than one of an unusual frequency, such as 8.34289 MHz. Moreover, for thickness-shear crystals, such as the AT-cut and SC-cut, the lower the frequency, the lower the aging [48]. Since at frequencies much below 5 MHz, thickness-shear crystals become too large for economical manufacturing, and since all the highest stability oscillators use thickness-shear crystals, the highest-stability commercially available oscillator's frequency is 5 MHz. Such oscillators will also have the lowest phase noise capability close to the carrier. There are also some excellent 10-MHz oscillators on the market; however, oscillators of much higher frequency than 10 MHz have significantly higher aging rates and phase noise levels close to the carrier than do 5 MHz oscillators. For lowest phase noise far from the carrier, where the signal-to-noise ratio determines the noise level, higher-frequency crystals (e.g., 100 MHz) can provide lower noise because such crystals can tolerate higher drive levels, thereby allowing higher signal levels.

F. Failure Mechanisms

Crystal oscillators have no inherent failure mechanisms. Some have operated for decades without failure. Oscillators do fail ("go out of spec") occasionally for reasons such as:

- Poor workmanship and quality control—e.g., wires that come loose at poor-quality solder joints, leaks into the enclosure, and random failure of components
- Frequency ages to outside the calibration range due to high aging plus insufficient tuning range
- TCXO frequency vs temperature characteristic degrades due to aging and the "trim effect," and OCXO frequency vs temperature characteristic degrades due to shift of oven set point.
- Oscillation stops or frequency shifts out of range or becomes noisy at certain temperatures, due to activity dips
- Oscillation stops or frequency shifts out of range when exposed to ionizing radiation, due to use of unswept quartz or poor choice of circuit components
- Oscillator noise exceeds specifications, due to vibration induced noise
- Crystal breaks under shock, due to insufficient surface finish.

G. Specifications, Standards, Terms and Definitions

There are numerous specifications and standards that relate to frequency control devices. The major organizations responsible for these documents are the Institute of Electrical and Electronics Engineers (IEEE), the International Electrotechnical Commission (IEC), the International Radio Consultative Committee (CCIR), and the U.S. Department of Defense, which maintains the Military Specification (MIL-SPEC) system. A listing of "Specifications and Standards Relating to Frequency Control" can be found in the final pages of the *Proceedings of the IEEE Frequency Control Symposium* and its predecessor, the *Proceedings of the Annual Symposium on Frequency Control*. In the 1996 *Proceedings*, for example 79 such documents are listed [75]. Many of the documents include terms and definitions, some of which are inconsistent. Unfortunately, no single authoritative document exists for terms and definitions relating to frequency standards. The terms and definitions in the CCIR glossary [47], in IEEE Std. 1139 [51], and in MIL-O-55310s Section 6 [59] are the most recent; they address different aspects of the field, and together form a fairly good set of terms and definitions for users of frequency control devices.

The most comprehensive document dealing with the specification of frequency standards is MIL-O-55310 [59]. The evolution of this document over a period of many years has included periodic coordinations between the government agencies that purchase crystal oscillators and the suppliers of those oscillators. The document addresses the specifications of all the oscillator parameters discussed above, plus many others. This specification was written for crystal oscillators. Because the output frequencies of atomic frequency standards originate from crystal oscillators, and because no comparable document exists that addresses atomic standards specifically, MIL-O-55310 can also serve as a useful guide to specifying atomic standards.

MIL-STD-188-115, *Interoperability and Performance Standards for Communications Timing and Synchronization Subsystems,* specifies that the standard frequencies for nodal clocks shall be 1 MHz, 5 MHz, or 5×2^N MHz, where N is an integer. This standard also specifies a 1-pulse-per-second timing signal of amplitude 10 V, pulse width of 20 μs, rise time less than 20 ns, fall time less than 1 μs; and a 24-bit binary coded decimal (BCD) time code that provides Coordinated Universal Time (UTC) time of day in hours, minutes, and seconds, with provisions for an additional 12 bits for day of the year, and an additional four bits for describing the figure of merit (FOM) of the time signal. The FOMs range from BCD character 1 for better than 1 ns accuracy to BCD character 9 for "greater than 10 ms of fault" [76].

IV. Related Devices

A. Crystal Filters

Quartz crystal units are used as selective components in crystal filters [77]. With the constraint imposed by the equivalent circuit of Fig. 3, filter design techniques can provide bandpass or bandstop filters with a range of characteristics. Crystal filters exhibit low insertion loss, high selectivity, and excellent temperature stability.

Filter crystals are designed to have only one strong resonance in the region of operation, with all other responses (unwanted modes) attenuated as much as possible. The application of energy-trapping theory [39,77] can provide such a response. If electrode size and thickness are selected in accordance with that theory, the energy of the main response is trapped between the electrodes, whereas the unwanted modes are untrapped and propagate toward the edge of the crystal resonator, where their energy is dissipated. It is possible to manufacture AT-cut filter crystals with greater than 40-dB attenuation of the unwanted modes relative to the main response.

Filters made of piezoelectric ceramics, usually of PZT compositions, cover the range of about 50 Hz to above 10 MHz. As is the case for quartz filters, these devices range from simple resonators to multielectrode resonators to coupled sets of devices. PZTs, having a high coupling coefficient and moderate Q, allow the use of these devices in medium- to high-bandwidth applications. Ceramic filters have poorer frequency vs temperature and long-term stability than do quartz crystal filters.

SAW bandpass filters are used in applications such as television receiver intermediate frequency circuits. Such filters can provide stop-band rejection of better than 60 dB and in-band response flat to 0.1 dB. SAW devices can also perform signal processing functions, such as pulse compression and side-lobe suppression that can be performed by dispersive filters and reflective array compressor (RAC) filters, and a chirp transform can provide the Fourier transform of an input signal.

B. Sensors and Transducers

Whereas in frequency control and timing applications of quartz crystal devices the components are designed to be as insensitive to the environment as possible, resonators made of quartz crystals (and of other piezoelectric materials) can also be designed to be highly sensitive to environmental parameters such as temperature, mass changes, pressure, force, and acceleration. The sensitivity of resonators to mass loading has been exploited in chemical and biological sensors. The sensor applications of piezoelectric resonators were the subjects of special sessions at the 1997 IEEE International Frequency Control Symposium [75] and is the subject of a special issue of the *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* [78].

Quartz crystal transducers can exhibit unsurpassed resolution and dynamic range. For example, one commercial "quartz pressure gage" exhibits a 1-ppm resolution, i.e., 60 Pa at 76 MPa (0.01 lb/in^2 at 11,000 lb/in^2), and a 0.025% full-scale accuracy. Quartz thermometers can provide microdegrees of resolution and millidegrees of absolute accuracy over wide temperature ranges. Quartz sorption detectors can detect a change in mass of 10^{-12} g. Quartz accelerometer/force sensors are capable of resolving 10^{-7} to 10^{-8} of full scale.

Piezoelectric ceramics are also used for sensors. In some applications, ceramics (e.g., various compositions of lead zirconate titanate, PZT) are preferred over quartz and other single crystal piezoelectrics due to their higher piezoelectric coupling, which can result in a larger signal when a force is applied. For example, ceramics are used in some accelerometers wherein the acceleration of a mass applies a compressional or shear force to the piezoelectric ceramic. The signal conditioning circuitry, which must amplify what is usually a small signal from a high-impedance source, is often part of the device.

V. For Further Reading

Reference 34 contains a thorough bibliography on the subject of frequency standards to 1983. The principal forum for reporting progress in the field has been the *Proceedings of the IEEE Frequency Control Symposium* (which was called the *Proceedings of the Annual Symposium on Frequency Control* prior to 1992) [75]. Other publications that deal with frequency standards include *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on Instrumentation and Measurement, Proceedings of the Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting* [79], and *Proceedings of the European Frequency and Time Forum* [80]. Review articles can be found in special issues and publications [34, 81–85].

Frequency control information can also be found on the World Wide Web at www.ieee.org/uffc/fc.

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