FREQUENCY CONTROL

A Symposium report by ***A. D. Ballato*** *and* ***H. G. Andresen***

THE Sixteenth Annual Frequency Control Symposium, sponsored by the Solid State and Frequency Control Division of the U. S. Army Signal Research and Development Laboratories, was held on April 25, 26, and 27, 1962, in Atlantic City, N. J. Participating in the proceedings were over 500 representatives of industry, government agencies, and universities, from both the U. S. and abroad. Among the foreign nations represented were Germany, England, France, Canada, Sweden, and Japan.

The topics discussed ranged far and wide. Many ways were considered of extending the usefulness of frequency control systems in new directions, from the point of view of mechanically vibrating elements and by making use of molecular and atomic phenomena. A common interest and objective of those participating in the discussions is that of obtaining a stable source of frequency, or what is practically equivalent, a stable time scale. Other considerations, such as the range of frequencies, size and cost of this source, etc. have led to different solutions to the basic objective and at the same time to many problems associated with each solution.

AT the lower end of the frequency spectrum, from audio frequencies upwards to several hundred megacycles, a range of more than 20 octaves, the perennial choice for frequency-control purposes has been the mechanically resonant quartz crystal. It combines the attractive features of small size, direct connection to electrical networks by means of the piezoelectric effect, and a high-quality factor (Q) compared to purely electrical circuit elements.

Since the quality factor is largely responsible for the ability of a crystal to maintain a constant frequency when inserted in an appropriate circuit, much attention has been focused on the limitations placed upon this quantity by properties inherent in a material. Two such papers were presented. E. G. Spencer, R. T. Denton, and R. P. Chambers of the Bell Telephone Laboratories discussed the effects of microwave acoustic losses in yttrium-iron garnet, finding at room temperatures both a low acoustic loss and a strong transducer action, indicating its potential usefulness in acoustic devices. Application of this material for frequency-control purposes awaits investigation of its temperature characteristics and, particularly, whether an orientation exists with a small temperature coefficient. Furthermore, the dependence of resonance frequency on the applied magnetic field remains to be determined.

A. D. Ballato and H. G. Andresen are members of the staff of the US Army Signal Research and Development Laboratory at Fort Monmouth, N. J.

The causes of internal friction in crystal resonators were the subject of a study by E. Hafner of USASRDL. He told of attempts to determine the ultimate quality factor obtainable in a crystal with a nearly perfect lattice structure and identified the nonlinearities in the elastic constants as the phenomenon responsible for limiting the Q in crystals free of defects. An estimate for the magnitude of the room-temperature acoustic attenuation in terms of the thermal conductivity led him to the discovery that the amount of heat which can be transported at normal temperatures by acoustic modes is orders of magnitude below that actually observed in a real crystal. He maintained that, once the role of the optical lattice vibrations in the thermal-conduction phenomenon has been clarified and the electromagnetic interaction between the atoms included in the theory, it will be possible to obtain a close estimate of the intrinsic acoustic attenuation in a given dielectric crystal from its measured optical and thermal properties.

The presence of loss in a vibrating crystal element lowers the Q, and thereby increases the ambiguity in the frequency to be determined. There are also several other evils to which it falls heir, not the least of which are the frequency excursions caused by temperature variations, radiation, circuitry changes, and the influence of external forces. Another undesirable contribution is caused by the phenomenon of aging—a frequency drift which is a function of time and of the environmental history of the element. R. B. Belser and W. H. Hicklin of Georgia Institute of Technology reported on the aging of quartz resonators at fundamental and overtone modes, with comments on radiation effects. The resonators were made of both natural and synthetic quartz, and it was found that the overtone modes of operation sometimes showed aging patterns different from the fundamental; the percentage aging at the third and fifth overtones was often less than that at the fundamental for the same resonator. The saturation effects of gamma irradiation at a dosage of 1.6×10^6 rad/sec for periods up to 24 hours indicate that quartz resonators usually exhibit positive frequency shifts. Subsequent aging rates following the saturation irradiation are small compared to those obtained for irradiation periods of a few minutes at the same dose level. The frequencies of the irradiated resonators tend to stabilize after storage for a few days at 85°C.

Radiation effects were also studied by J. C. King and D. B. Fraser of the Bell Telephone Laboratories to determine the effects of reactor irradiation on thickness shear crystal resonators. A clear relationship between radiation and acoustic absorption, aging, and the frequency-temperature characteristic was demonstrated, when natural and synthetic AT-cut quartz resonators were exposed to an integrated fast (> 0.1 MeV) neutron flux of 1.2×10^{18} nvt over a period of 46 days. The resonance frequency and Q of crystals at 1, 3, 5, and 9 mc were monitored during irradiation. These parameters were also measured as a function of temperature from 4.2°K to near the α-β inversion point of quartz (573°C) after irradiation and then again after they were annealed at 500°C for several days.

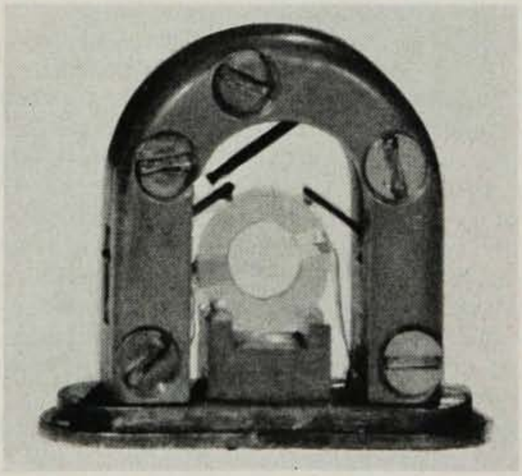
The resonance frequency was found to increase linearly with reactor irradiation to a value (measured at room temperature) of approximately 900 parts per million. At the same time, the Q of the crystals decreased linearly to nearly a decade below the pre-irradiation value. A most unexpected result was found upon annealing irradiated crystals which had previously been subjected to thermoelectric treatment. It turned out that the high-temperature Q (around 500°C) of such crystals was substantially higher than ever observed before. The sequence of high-temperature sweep, pile irradiation, and high-temperature anneal apparently causes some of the lattice defects which degrade the Q around 500°C to become inactive.

W. J. Spencer and W. L. Smith of Bell Telephone Laboratories, discussing the performance of crystal units operating under severe environmental conditions, reported that rugged frequency-control devices for satellite and missile applications have been developed. These devices employ miniature AT quartz-crystal units in transistorized high-efficiency circuits, and operate in the frequency range from 10 to 150 Mc. The performance of the crystal units during vibration, acceleration and thermal cycling was reported. The effect of irradiation similar to that experienced in the Van Allen Belt on the resonant frequency of some units was found to be of the order of 5 parts per million.

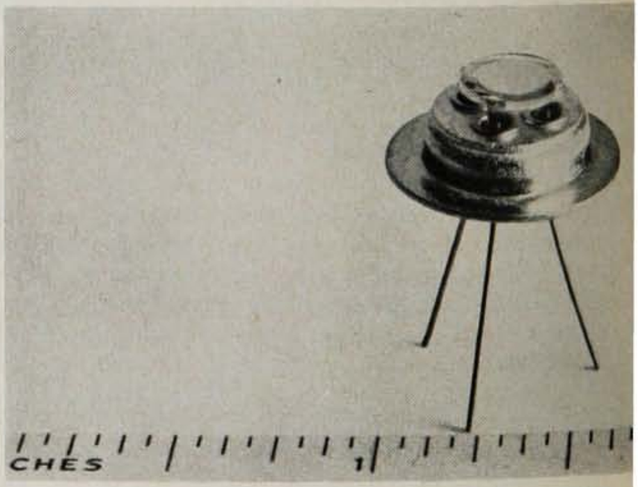
An effect which is recently receiving attention is that of external forces and torques on the frequency of vibrating plates. In a basic study motivated by a need to reduce the influence of shock and vibration associated with high-acceleration vehicles such as aircraft, guided missiles, and satellites, C. R. Mingins, L. C. Barcus, and R. W. Perry of Lowell Technological Institute are developing a theory to account for the observed frequency excursions of a plate when a force is applied to its edge. This is a continuation of work originally begun at the Army Signal Research and Development Laboratories. For AT-cut plates, two critical angles are found where a diametric force induces no change in frequency. These angles are found to be invariant with the frequency and with the magnitude of the force applied in the range considered. For BT plates the frequency deviations are negative for all angles, but possible techniques appear to be available to produce insensitivity at certain angles. These include the application of a flexural stress.

An enterprising adaptation of these observations was reported by R. J. Munn of Motorola who, in continuing work begun by the Signal Corps, described how the temperature effect on frequency could be compensated over a wide range by using bimetallic arms to apply temperature-dependent compressive forces to the crystal.

The frequency-temperature behavior of a quartz resonator is determined primarily by the variation of the elastic constants with temperature, the expansion coefficients, and the manner in which the resonator is vibrating. Early attempts at reducing the temperature coefficient of thickness-mode resonators led from an unrotated Y cut to the AT and BT cuts, each having a single rotation with respect to the crystal axes. To reduce the temperature effect further, quartz cuts having two rotations were investigated by R. Bechmann, A. D. Ballato, and T. J. Lukaszek, who determined the first-, second-, and third-order temperature coefficients of the elastic constants of quartz and investigated the general family of doubly rotated cuts, including the newly dis-



Temperature-compensated crystal; bimetallic arms apply temperature dependent pressure to effect a frequency balance.



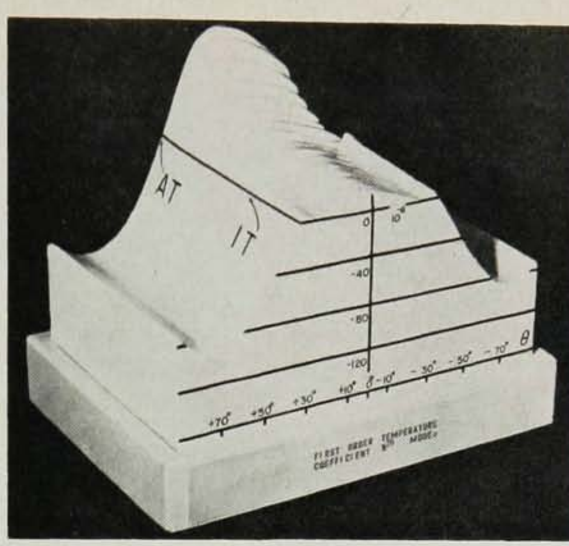
Quartz crystal mounted in transistor enclosure. Rugged units of this type are suitable for use in satellite and missile environments.

covered RT cut which is very insensitive to wide temperature variations.

A conventional way of reducing the frequency change caused by a change in ambient temperature is to place the crystal unit in an oven and operate it above the ambient temperature. A new approach to the oven problem was described by T. D. Merritts and J. C. Taylor of Westinghouse Electric Corp. Their solution involves thermoelectric temperature control of the crystal environment. Since the Peltier effect is reversible in character, a thermoelectric chamber can be operated either as a cooling or heating device, depending on the direction of input current flow. By means of this reversible effect, the internal chamber temperature, which surrounds temperature-sensitive components such as quartz crystals and crystal oscillators, can be controlled and maintained at 25°C, as the external ambient temperature varies either above or below the controlled temperature point. Since the crystal is able to operate at a lower temperature than if kept in an oven above ambient, the aging rate will be lower, and improved frequency-temperature stability and reduced average power consumption can result under certain operating conditions.

The areas of frequency generation and stabilization are not the only ones in which the quartz element finds application. The passive role of selection is also well suited to its capabilities. When a crystal is to be used in this manner (as a filter component, for example), an additional requirement is placed upon its performance. Whereas an ordinary mechanically vibrating element might exhibit a variety of undesired resonances in the vicinity of the main mode as a result of reflections from the boundaries, coupling, etc., resonators for filters are required to be substantially free from these unwanted modes. The sharp selectivity, low insertion loss, and small size of crystal filters have generated a new concept in frequency selectivity which makes it well worth while to explore techniques for eliminating undesired modes. Crystal and crystal-filter technologies have been advancing quite rapidly in the past few years for frequencies lying between 1 Mc and 30 Mc. Crystal filters at various frequencies below 30 Mc easily offer band-pass and single-sideband characteristics that were at one time considered to be unattainable. The performance of crystal filters at these frequencies has led to speculation about the possible filter-propagation characteristics realizable in the vhf region between 40 Mc and 75 Mc. These were the subject of an investigation by S. Malinowski and D. Schennberg of Motorola Inc., who designed, constructed, and evaluated crystal filters utilizing crystals in third overtone operation. Filters at 40 Mc, 60 Mc, and 75 Mc with 6-dB pass-bandwidths of 50 kc and 250 kc, and 60-dB rejection bandwidths of 100 kc and 500 kc, respectively, were shown to be practical.

Another approach to the subject of high-frequency quartz-crystal filters was provided by Y. Nakazawa of Toyo Communication Equipment Co., Ltd. Here, the presence and prominence of one vibrational mode in



Three-dimensional model showing first-order temperature coefficient of lower shear mode for quartz as function of orientation. Zero locus defines a family of low-temperature coefficient cuts; two widely used cuts are indicated.

the crystal existing near the main mode, and usually classed as undesired, is employed with the main mode to provide the two resonances necessary for the construction of a band-pass filter from a single vibrator. The method of suppressing the unwanted frequencies and the relation between the dimensions of 10.7 Mc AT-cut crystal blanks and band-pass widths of from 10 to 40 kc were discussed. The new high-frequency mechanical filters realize a considerable reduction in weight and size of the units and are claimed to be amenable to mass production.

The problem of measuring the parameters of a high-frequency filter crystal is as important as being able to manufacture it in the first place. If the job of measurement cannot be done with sufficient accuracy, then the resulting filter cannot be expected to perform according to design specifications. The mechanically vibrating resonator operating in the vicinity of its resonance point is equivalent to a purely electrical circuit of constant element values consisting of a series RLC arm shunted by another capacitance; it is convenient from an electrical standpoint to characterize the mechanical resonance in terms of these element values. At higher frequencies the presence of stray capacitance and distributed inductance interferes with the measurements of these values. F. K. Priebe of the Army Signal Research and Development Laboratory presented a technique to overcome these difficulties. By means of a Schering bridge and a highly stable frequency synthesizer, readings of effective capacitance and resistance due to the crystal are taken as a function of frequency in the region near resonance. From these readings all parameters of interest to the filter designer may be determined. The method offers high accuracy, extends to very high frequencies, and is usable by filter-crystal manufacturers.

In the discussion above, we have been talking of the quartz crystal resonator as a frequency-control element, of the reasons why it may be induced to change its frequency, and what is being done to correct or eliminate these shortcomings. But it is not only the crystal which should bear attention in this regard. A vibrating crystal unit is only a part of an oscillator; the other circuit elements play a role in determining the constancy of the frequency source.

C. Abom of the Swedish Defense Ministry traced one source of frequency instability in oscillators to the cathode interface of the oscillating tube, demonstrating the need for cathodes with coatings of high purity. He also discussed the relationship of long-term drift of the frequency to changes in the interface layer. The effects of noise on oscillator frequency stability were discussed by E. Hafner of the Army Signal Research and Development Laboratory, and L. Saporta and G. Weiss of New York University. This paper presented a study of the scatter in frequency of a fixed sine wave perturbed by various narrow-band noise spectra. The spectra considered are characteristic of white noise shaped by one- and two-stage parallel RLC networks and a Gaussian network. Linear models were analyzed in which the noise is added to a fixed sinusoid in one of two ways. In the first, the simple instantaneous addition of the noise and signal is considered. The frequency scatter of the composite signal was shown to be similar to that which would be obtained if the noise were to phase-modulate the signal. The second type of noise addition is made in the cumulative or random walk sense. In this case the statistics are similar to those for frequency modulation by the noise.

REVIEWING the topics of the papers presented in the field of atomic and molecular frequency standards, one gets the impression that a fast and exciting seven-year development period has come to a momentary rest. In this period the cesium-beam frequency standard, the ammonia maser and the gas-cell frequency standards have been investigated and technically developed. For these frequency standards most of the future work will be devoted to circuitry simplification, reduction of size, and reliability improvement. At present, the cesium-beam frequency standard can be looked upon as the most precise primary frequency standard: its frequency instability is of the order of some parts in 10^{-12}, and its absolute frequency can be defined with an accuracy of some parts in 10^{+11}!

Most of the papers of this year's Frequency Control Symposium were theoretical in nature or presented results of preliminary experimental studies; no conclusive experimental data have been presented to show that the instability of frequency standards can be pushed below the one part in 10^{-12} limit just now. Some of the papers presented specialized in the theoretical analysis of effects that might limit the performance of atomic and molecular frequency standards, others were devoted to the study of completely new experimental methods to increase the stability and accuracy of frequency standards up to the $1:10^{+13}$ region, or even better.

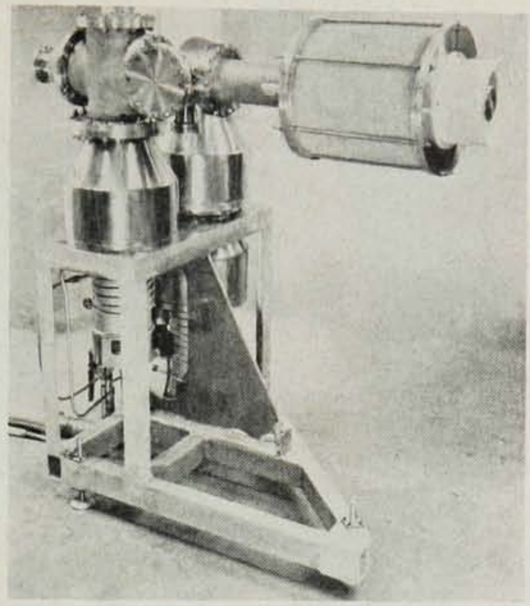
M. Mizushima, Colorado University, discussed in his paper the theory for the experimentally known effect of atomic-resonance frequency shifts resulting from the influence of the radiation field. The theory was formulated in terms of a quantized electromagnetic field and predicts energy-level shifts which, in second-order approximation, are independent of time, so that the exciting electromagnetic field will change the atomic-resonance frequency slightly. It should be mentioned, however, that this effect will not seriously influence the performance of the cesium-beam standard, since the power of the microwave excitation, used in the cesium standard, is at least two orders of magnitude smaller than the field intensity necessary to cause a radiation-field frequency shift of the order of some parts in 10^{-11}!

The performance of atomic frequency standards is essentially influenced by the line shape of the atomic reference transition. The paper of I. Senitzky of the Army Signal Research and Development Laboratory analyzed the modification of the spectral distribution of induced and spontaneous emission of a molecular beam passing through a cavity, by taking into account the presence of amplification. Formulae for the spectral distribution have been derived for the case in which the molecular transit time is short compared to the radiation lifetime of the molecule.

In order to improve the stability and accuracy of atomic frequency standards, there is an obvious tendency to choose frequency references having as high a Q-value as possible. Since the Q-value of any resonance structure can be defined by the ratio $Q = f/\Delta f$, there exist two experimental possibilities to increase the Q-value: either one tries to reduce the linewidth, or one has to increase the resonance frequency f. Both methods are being pursued in order to improve the performance of atomic frequency standards. Since the linewidth is inversely proportional to the interaction time between the rf field and the atom, linewidth reductions in conventional atomic-beam experiments will necessarily be limited by the length of the beam apparatus. Because of this limitation, resonance linewidths, obtainable with conventional beam techniques, are practically limited to some 100 cycles per second. The successful operation of a hydrogen maser by the group of N. F. Ramsey at Harvard University, however, proved the feasibility of an ingenious experimental technique to get around this general problem. A beam of hydrogen atoms is directed into a "bouncing chamber" which is located inside a cavity, resonating at the hydrogen resonance frequency of 1420 Mc/sec. The interaction time with the rf field will then be determined either by the finite radiation lifetime due to wall collisions or by the time constant that describes the particle loss because of diffusion effects. By coating the walls of the bouncing chamber with a thin film of teflon, it is possible to arrive at interaction times up to 2 seconds, corresponding to a linewidth of less than 1/10 cycle per second and a resonance Q-value of larger than 10^{10}! In his paper N. F. Ramsey discussed the potential properties of a hydrogen maser as a high-precision frequency standard. Because of the extremely high Q-value, excellent short-term stability can be expected. The long-term stability, however, will be essentially determined by external effects: the cavity must be very well shielded against stray magnetic fields (stray fields should be reduced to the order of 10^{-4} oersted) and the "cavity pulling" effect has to be reduced by a careful stabilization of the cavity temperature and the air pressure. Measurements of beat notes between two hydrogen-maser frequencies resulted in frequency instabilities of the order of some parts in 10^{-12}. Since the measurements were performed without temperature and air-pressure stabilization, these data indicate that the ultimate frequency instability of a hydrogen maser can be expected to be $1:10^{-13}$ or even less.

Another possibility to increase the Q-value is to increase the resonance frequency while leaving the interaction time constant. The construction of a frequency standard, operating in the mm-wave region, encounters some problems, since there exist neither a detailed knowledge of the hyperfine-structure splittings of molecular energy levels, nor proper mm-wave techniques to excite molecular beams. J. Gallagher, R. G. Strauch, R. E. Cupp, and J. W. Dees from the Martin Company, Orlando, Fla., described in their paper investigations being made on excitation and detection techniques for mm-wave transitions which can be used to develop frequency-control systems operating in the region of 200 $\rightarrow$ 300 kMc. Until now most emphasis has been placed on the generation of phase-locked mm waves. At 168 kMc phase-stable mm-wave power of approximately 15 μ watts was obtained by multiplication from a 24-kMc klystron which was phase-locked to the 241 200 harmonic of a phase-stable 100-kc oscillator. By phase-locking of a 100-kMc klystron, which has been already proved to be feasible, phase-stable mm-wave power in the order of some μ watts, can be obtained in the 200 $\rightarrow$ 400 kMc region. This power is sufficient for optimal excitation of molecular-beam resonances.

Pushing the frequency of the oscillator to the extreme limit, one arrives at the optical-maser oscillator. A. Javan, Massachusetts Institute of Technology, presented a very interesting paper about the frequency characteristics of He-Ne optical masers as measured through observation of the beat notes between two independently oscillating masers. In order to discuss the frequency stabilities of optical masers, it must be mentioned that in the optical region the oscillation frequency is not determined by atomic properties but mainly by the properties of mechanical resonance structures. At optical frequencies the situation is just reversed as compared to the microwave region: the oscillation frequency of microwave masers is mainly determined by the atomic or molecular resonance and the influence of the cavity will shift this frequency only slightly because of the "cavity-pulling" effect. In the optical region the Q-value of the mechanical structure is large compared to that of the atomic structure, so that the oscillation frequency will be mainly determined by mechanical properties. Thus the long-term stability of optical-maser oscillators must necessarily be relatively bad. By locking the mechanical resonance structure to the maximum of the optical line, the long-term stability of the optical-maser frequency can be improved. Since the Q-value of an optical-reference resonance is much smaller than those of atomic references in the microwave region, this technique will certainly not show any performance improvement as compared to existing frequency standards. A. Javan pointed out, however, that according to the high optical-maser frequency a good short-term stability is already sufficient to perform some high-precision optical-interference experiments. Beat-note experiments between two independently oscillating optical masers indicated that short-term frequency stabilities of the order of some parts in 10^{-14} can be expected.



Experimental model of a hydrogen maser constructed by Ramsey's group at Harvard.

Further improvement of the stability and accuracy of frequency standards will not only improve, for instance, the accuracy of Doppler-shift measurements for navigation, guiding, and tracking purposes, but will also lead to the possibility of new and fundamental physical experiments. R. H. Dicke, Princeton University, discussed the possibility of measuring a slight decrease of the gravitational interaction with time as predicted by Dirac and others. A steady decrease with time of the gravitational interaction would result in an artificial satellite running slower with time when compared with an atomic clock. Taking into account the precision of present atomic-frequency standards, as well as the accuracy that can be obtained by measuring the satellite position with optical-maser light pulses, it would be necessary for the satellite to be in orbit for a year or two before sufficiently accurate results would be obtained to determine whether the gravitational constant is actually decreasing with time.