Report on the 19th annual symposium . . .

FREQUENCY CONTROL

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Specialists in frequency control are improving their crystal vibrators and atomic frequency standards. Toward better crystal devices, they are making filter crystals that operate above 30 Mc/sec; with better mathematical analysis of vibration modes to help, they are using electrode-thickness tuning and crystal shaping to improve crystal response; they are using sound waves and x rays to investigate vibration-mode patterns. Some are seeking new materials to replace quartz, especially endowed by nature to function as a frequency standard. Others have used quartz in a new way to make a new kind of delay line. Toward better atomic frequency standards, they are improving both stability and accuracy. All-solid-state versions are making rubidium gas-cell standards and cesium-beam standards more useful. Other improvements in atomic devices include better circuits for hydrogen-beam tubes, narrower reference lines, and better frequency stabilities, both long- and short-term.

Among the various subjects discussed at the Nineteenth Annual Symposium on Frequency Control last spring, work with crystal vibrators and atomic standards was of greatest interest for physicists. The meeting drew some 600 participants to Atlantic City in mid-April. It was, as usual, sponsored by the US Army Electronics Laboratories of Fort Monmouth, N. J.

Crystal vibrators

For crystal resonators, the specific area of greatest advancement lies in development of crystals for filter application in the region above 30 Mc/sec. These units differ from conventional oscillator crystals primarily in having to be substantially free from undesired resonances near the main thickness-shear mode.

For frequencies above about 10 Mc/sec, beveling and contouring become unimportant and the vibrator consists of a flat plate structure with electrodes for excitation deposited directly on the quartz. It was observed some years ago at USAEL that unwanted resonances of these plates were attenuated when the electrode diameter bore a certain ratio to the plate thickness governing the frequency. Applying this criterion to the design of filter crystals, however, meant that as one goes up in frequency the corresponding electrode size required becomes smaller and smaller, until the insertion loss increases beyond the point of usefulness. Further progress along these lines was possible only after it was shown that the electrode thickness was a significant additional parameter affecting the mode spectrum. G. K. Guttwein of USAEL reported experimental evidence on this in 1963, and, concurrently, W. S. Shockley of Clevite Corporation gave a qualitative explanation of the influence of both electrode size and thickness by employing a concept of "energy trapping" and establishing an analogy between cutoff in a waveguide and in an acoustic plate supplied with electrodes. The theory was further developed at the 1964 symposium by R. D. Mindlin of Columbia University and by D. R. Curran and D. J. Koneval of Clevite Corporation.

Investigations continue to be active in this area, and this year Mindlin reported further progress in bringing vibrational behavior of crystal plates under manageable mathematical analysis. The line of investigation initiated last year has now been extended to the fundamental thickness-twist mode and its anharmonic overtones with equally good

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In the two decades during which the US Army has conducted its annual frequency-control symposia, electromagnetic oscillations from atoms in transition have joined mechanical vibrations of crystals as frequency standards. Masers, in which hydrogen, ammonia, or rubidium is the active medium, and cesium beams function alongside quartz oscillators. Current developments are turning both crystal and atomic standards into more accurate and easier-to-use devices.

results. Explicit expressions, in terms of dimensions and physical properties of electrodes and crystals, are now available for the empirical coefficients appearing in the formulas of Curran and Koneval.

If the frequency at resonance is less than the thickness-shear cutoff of the uncoated part of the plate, no thickness-shear or thickness-twist waves escape from the region under the electrodes. These modes, however, are coupled elastically with flexural and face-shear waves which do escape. Mathematical solution of this problem reveals that the resulting energy loss is an almost periodic function of the ratio of electrode length to thickness t of the plate. The periods are about $1.6t$ for flexural waves and $3.0t$ for face-shear waves, exact values depending on electrode mass. The quality factor Q, assuming no other loss mechanism, ranges from maxima exceeding 10^8 to minima of about 10^4, the minima diminishing with reduction in electrode length. This means that in addition to suppressing unwanted modes, electrodes of the proper size result in an improved quality factor for the desired response. The first-order approximate equations used in these studies do not accommodate harmonic overtones. Contemplation of an eventual extension of the work to include harmonic overtones and anharmonic overtones associated with them led Mindlin to examine anew the full three-dimensional equations of crystal elasticity, whence he discovered exact solutions for all the coupled thickness-twist and face-shear modes in an infinite plate with the elastic symmetry of the rotated Y cuts of quartz—with and without electrodes. These solutions can now serve as a basis for the formulation of nth order approximate equations of motion that can be solved for finite plates.

With the mathematical problem apparently reasonably well under control, the question of practical utilization was quickly answered by Curran and Koneval (Clevite) and by T. J. Lukaszek (USAEL). Curran and Koneval have applied energy-trapping theory to devise several new resonator structures applicable to both fundamental- and harmonic-mode crystals in the VHF range. One of these, the "inverted mesa" resonator, looks particularly promising for frequencies above 100 Mc/sec. In this configuration, electrodes thick enough to have a low electrical resistance are used, but they are partially embedded in the quartz wafer to obtain the desired frequency lowering. In practice, the electrodes would be deposited in a depression in the quartz wafer, or else the thickness of the surrounding unelectroded wafer would be increased by depositing a low-loss dielectric such as silicon monoxide. In either case, the net frequency lowering is adjusted to that required by electrode dimensions.

Curran and Koneval took a further step in making the design of filter crystals amenable to simple calculation by advancing a transmission-line model of a quartz wafer to account for the propagation properties of various modes over wide frequency ranges. The results show a relation between resonator design and network design, which should be considered to insure satisfactory filter performance.

Lukaszek drew upon the Columbia and Clevite work in designing his experiments. Faced with filter requirements extending above 100 Mc/sec and calling for resistances of less than 100 ohms and at least 40 db suppression of unwanted modes, he selected fifth-overtone blanks in the 70-112-Mc/sec range and calculated the electrode sizes that would achieve the resistance specifications. By varying electrode thickness in steps he showed that an optimal deposition exists for various combinations of electrode diameter and plate frequency. Near the best values the curves are not too steep, allowing the designer a certain latitude in the range of motional resistance and capacitance he can specify for his filters. The result lightens the burden on the manufacturer too, for he can still use electrode mass for final frequency adjustments, although within somewhat narrowed limits. A before-and-after comparison of the response of a narrow band (16 kc/sec) filter at 112 Mc/sec shows that previous crystals, because of their unwanted mode content, produced undesired bands of transmission less than 0.1 percent from the passband; substitution of crystals designed by the new technique repressed all spurious responses more than 50 db and decreased the insertion loss substantially.

It can be expected that further application of the theory will yield useful vibrator designs well into the upper VHF region. Several serious problems remain, however, including those of dependence of Q on structural defects and details of fabrication and mounting, as well as a general decrease in Q with increasing frequency.

In view of the complexity of the theoretical problem of vibrations in plates, even when limited to defect-free homogeneous continua subject to the simplest boundary conditions, one must have experimental methods for "seeing" the actual patterns of vibration in our less-than-perfect, finite wafers. One such method is provided by x-ray diffraction, where local strain gradients within the crystal-lattice intensity modulate the image. These gradients can be produced by defects such as dislocations or interstitial impurities and by mechanical vibrations.

The Georgia Tech group, composed of R. A. Young, R. B. Belser, A. L. Bennett, W. H. Hicklin, J. C. Meaders, and C. E. Wagner, is currently conducting vibration-mode studies with these x-ray imaging techniques. They study location, shape, and distribution of activity in the oscillating region of the crystal and some other aspects of the ultrasonic standing waves such as wavelength, propagation direction, polarization, nodal positions, and coupling among modes. Parameters of special interest are type of cut, defect type and distribution, electrode material and distribution, and drive level. They reported that internal defects can sometimes be present in considerable degree without an apparent ill effect on the frequency-time behavior. On the other hand, specific combinations of defect type, distribution, and orientation relative to the standing waves in the oscillator can significantly distort the normal distribution of vibrational energy. Both distortion of normal patterns and enhanced mode coupling can be induced. This finding has the practical consequence of placing some of the onus for the crystal behavior on clips and mounting cements that anchor the crystal in the holder.

X-ray diffraction topography was also discussed by W. J. Spencer and K. Haruta of Bell Telephone Laboratories, who have complemented the Georgia Tech work by developing methods of determining actual magnitude of strain components on various crystallographic planes of the resonator. With diffraction from the various planes one can map the strain throughout the entire volume of the vibrating plate.

In the search for means of improving resonators and extending their frequency capabilities one of the most alluring possibilities remains the discovery of a new material to substitute for quartz. Nature has been so generous to quartz, however, that the task has always been difficult. A. W. Warner of Bell Laboratories reported on recent progress with new piezoelectric materials. These are a group of refractory oxides grown from a melt ($\sim 1600°C$) in the form of large single crystals. Among these are lithium gallium oxide, lithium aluminum oxide, lithium niobate, lithium tantalate, and calcium pyroniobate. These oxides are interesting because they are hard substances like quartz and can be treated similarly. The crystal symmetries are such (C_{2v}, D_4, C_{3v}, C_{3v}, C_{6v}) that zero temperature coefficients are likely, and the crystals can be grown without undue difficulty. The investigations are not yet complete but indicate that coupling factors higher than 50 percent with lithium niobate and 30 percent with lithium gallium oxide may be realized, and Q values may rival those of quartz (10^5 at 100 Mc/sec). High coupling factors make these materials attractive for a variety of applications, notably wide-band filters.

G. A. Coquin of Bell Laboratories considered crystalline quartz as the delay medium for a new type of delay line that can be used to synthesize a filter response. In operation, a signal pulse to the input transducer excites a disturbance with a spectrum of frequencies that propagate down the quartz delay strip as a group of surface waves. These waves interact with the quartz through the piezoelectric effect to produce a wave of polarization on the surface. This charge, in turn, is picked up by an array of electrodes arranged according to the Fourier transform of the desired filter characteristic. The interaction of the surface waves and the electrodes effects a convolution to produce the desired response at the output. Although best suited for highly dispersive filter applications, these tapped delay lines are also capable of performing as nondispersive filters, particulary in the 30–300-Mc/sec range.

Atomic frequency standards

Two general trends are characteristic of work with atomic frequency standards: conversion of these standards from sophisticated laboratory instruments into practical, reliable, easy-to-operate units, and improvement in frequency stability and accuracy.

The "oldtimers" of the atomic frequency standards (cesium-beam tubes, rubidium gas cells, hydrogen masers) are definitely no longer restricted to laboratory applications; engineering effort dur-

ing the past few years has successfully converted them into frequency standards for practical use. In particular, reliability, ruggedness, small size, weight, and power consumption of all-solid-state, militarized versions of rubidium-gas-cell and cesium-beam-tube standards are attractive features for commercial and military use, where utmost frequency stability and accuracy are required. A review of the status of the tri-service-sponsored militarized cesium-beam standard was presented at the symposium by S. Fast and others of National Company. They expressed confidence that long-term frequency instabilities smaller than 1 part in 10^{11} can be achieved for ambient temperatures, vibration, shock, and acceleration levels that fulfill military specifications.

Circuit engineering for improving hydrogen-maser performance is directed towards development of automatic cavity tuning. This would eliminate cavity pulling effects by tuning the maser cavity directly to either the hydrogen resonance or a frequency with precisely known offset from the resonance for which the cavity-pulling frequency shift can be predicted. If linewidth quenching techniques are used to determine the exact cavity tuning, problems can arise because of hydrogen-resonance frequency shifts that are associated with the line-width quenching process itself. An analysis of these linewidth-quenching-induced shifts of the maser frequency for various linewidth-quenching methods has been presented by one of the authors (H. G. Andresen, USAEL). For magnetic fields smaller than 10 mG, linewidth quenching by magnetic-field inhomogeneities (magnetic-relaxation quenching method) is experimentally convenient and shows promising features for application as the sensing method for an automatic cavity tuning system.

Various methods to improve the frequency stability of atomic frequency standards were discussed. One possibility for a cesium-beam-tube standard is to increase the signal-to-noise ratio of the detected atomic-reference resonance. This process allows "splitting" of the resonance line with higher precision, provided the electronic circuitry does not introduce additional frequency uncertainties. J. Halloway (Varian Associates) discussed performance tests of a novel cesium-beam optic with hexapole detection magnets and an indirectly heated annular-ring ionizer for the particle detection. Measured signal-to-noise ratios were a factor of ten better than those achieved with conventional dipole-deflection magnet design. It was pointed out by R. Sanborn (of Pickard and Burns, where the electronic circuitry for the signal-to-noise-ratio-improved cesium-beam tube is being developed) that further improvement of the spectral purity of the microwave excitation of the cesium resonance is necessary to take full advantage of this new beam-tube design.

Another alternative to improve frequency characteristics of atomic frequency standards is to increase the Q of the atomic reference resonance; Q is defined as $f/\Delta f$, where f stands for the resonance frequency and Δf for the linewidth of the atomic or molecular reference resonance. Two alternatives to increase Q, either by increasing the resonance frequency or by reducing the linewidth Δf were discussed by J. Gallagher and his colleagues from Martin Marietta and by N. F. Ramsey of Harvard. Gallagher reported the first experimental observation of Ramsey excitation patterns in the millimeter-wave region. Ramsey patterns have been observed for the $2_0 \rightarrow 2_2$ transition at 216 Gc/sec with 10-in. separation between the two excitation centers, consisting of parallel-plate Fabry-Perot resonators. The measured linewidth of the center Ramsey peak was 850 cps, which corresponds to a line Q of 2.5×10^8. A further increase of this Q by a factor of four appears feasible, although this result has not yet been achieved experimentally because of excessive stray electric and magnetic fields in the interferometer region. Considerable technical problems have to be solved, however, before these narrow resonance lines can be applied successfully for frequency control. The most serious problems are introduced by impurity of the exciting millimeter-wave spectrum, the relatively small signal-to-noise ratio for the detected resonance due to the inefficiency of the electron-bombardment ionizer and a small partition function due to multiplicity of molecular rotation levels and, finally, by phase instabilities between the two excitation centers. The experimental results indicated, however, Q's of the order of 10^9 can be achieved with molecular-beam machines in the millimeter-wave region, which nearly match the present Q record of 2×10^9 for the hydrogen resonance in the wall-coated storage bulb of a hydrogen maser. Ramsey saved the predominance of the ultimate line Q for the hydrogen maser by suggesting the interesting method of extending the hydrogen storage bulb to the outside of the maser cavity in order to enlarge the total storage-bulb volume and thus the bulb escape time. Analysis of maser operation for these experimental conditions shows the somewhat puzzling result that the maser will oscillate at power levels similar to those achieved with conventional storage-bulb arrangements but that the radiative lifetime and thus

Q for the resonance will increase and the wall shifts will decrease with increasing total volume of the storage bulb. This effect will produce improved frequency stability, accuracy, and resetability of the hydrogen maser. Although this technique offers fascinating possibilities for construction of a "super clock", size and magnetic shielding problems will limit practical exploitation. With these improved techniques, long-term frequency instabilities smaller than one in 10^{13} will soon be achieved with the hydrogen maser (even with conventional storage-bulb) and possibly also with an improved cesium-beam standard for frequency-averaging times of about an hour.

Although design emphasis in atomic frequency standards has so far been placed predominantly on achieving good long-term stability, attention has recently been focused on short-term stability. In this regard, active maser-type standards are far superior to passive arrangements such as beam-tube or gas-cell standards. The hydrogen maser combines good long-term and short-term stability, and either stability can be improved at the expense of the other. A comparison between long- and short-term frequency characteristics of hydrogen, rubidium, and ammonia masers was made by R. F. Vessot and colleagues of Varian Associates. Short-term stability is proportional to oscillation frequency and square root of output power; as a result, the short-term frequency performance of the ammonia maser should be twice as good as that of a rubidium maser, and both of these should be two orders of magnitude better than a hydrogen maser, which operates at relatively low output power and frequency. Because of its simplicity, small size, and "sealed-off" operation, the ^{87}Rb maser has promising features for applications, where short-term frequency stability is the primary need. In comparison with a hydrogen maser, the long-term stability of a ^{87}Rb-maser is significantly deteriorated by cavity-pulling effects, temperature dependence of buffer-gas-pressure shifts, and frequency shifts associated with optical pumping. A detailed analysis of optical-pumping effects on the ^{87}Rb oscillator was presented by P. Davidovits and W. A. Stern of Columbia. They suggested various schemes to eliminate the pumping-light influence on maser frequency. Since frequency shifts due to cavity pulling and temperature-dependent pressure shifts can, in principle, be matched to compensate each other, there is every reason to believe that further development of the ^{87}Rb maser will result in a small, practical frequency standard with good long-term and unsurpassed short-term frequency stability.