A STUDY OF THE PIEZOELECTRIC EFFECT
AND
THE CONSTRUCTION OF A SUPERSONIC GENERATOR

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A STUDY OF THE PIEZOELECTRIC EFFECT AND THE CONSTRUCTION OF A SUPERSONIC GENERATOR

I. INTRODUCTION

The remarkable development of the science of supersonics since World War I could possibly be compared to the advance made when it was first recognized that the interplay between light waves and matter furnished the key to the solution of many problems in molecular physics.

In the case of sound and light we, as individuals, have sharply marked limitations. The ear and the eye respond only to a limited range of vibration frequency. Just as we have ultra-violet, visible and infra red light, so also there is a sub-audible, audible, and supersonic sound.

Acoustics, up to 1917, was concerned almost exclusively with audible sound and its relation to speech, hearing, and music. In previous years Helmholtz and Lord Raleigh had apparently exhausted the subject, and only two discernible developments were taking place. These were the improvement of the telephone through the application of Raleigh's theories, and the development of practical methods for the improvement of acoustics in rooms, which was begun by W. C. Sabine at the beginning of the century. Up to this time, although vibrations beyond the audible range were known to exist, their potentialities were unsuspected. The intensive investigation of the properties of supersonic sounds has been largely a post-war development.

Acoustical vibrations are customarily divided into three not very sharply divided classes, based on the physiological process of hearing. In the first class are the sub-audible sounds, which consist of vibrations up to approximately thirty per second, and are of such low frequency that no pitch can be ascribed to them. The second class is the audible, or hearing, range and is composed of vibrations from approximately 30 to 20,000 per second. Above this limit is the third class, which is the region of supersonics. In this range, the sounds, even if of great intensity, produce no sensation of hearing, but give rise to many very surprising physical and biological phenomena which are not observed at lower frequencies.

II. HISTORY OF SUPERSONICS

A. Early Investigations of Inaudible Sounds

One of the earliest investigations to determine the highest pitch that could be recognized was made by Despretz in 1845, which set the limit at about 30,000 cycles per second. This was judged, however, not by actual measurement, but by estimates of musicians who claimed to be able to follow the number of octaves into the region of high frequency vibrations.

In 1899 Rudolph Koenig of Paris, by means of tuning forks only a few millimeters in length, was able to produce frequencies as high as 90,000. He determined the frequencies by Kundt's dust tube method, and may be regarded as the first person to make a study of supersonics.

Altberg in 1907 investigated the supersonic waves emitted by the spark discharge of a condenser and found that, what appears to be a single flash and crack, is in reality a very rapid succession of sparks. Each of these sparks produces a single acoustic air pulse, and the collection of these air pulses gives a wave train, of which the wavelength can be measured. He employed a diffraction grating made by parallel equidistant glass rods to measure the wavelengths, some of which he recorded as small as one millimeter (332,400 vibrations per second).

Shortly after this, Schultze made a careful study of the upper limit of the human ear. He made the measurements by employing two methods, the first being by the symmetrical patterns of fine grains of sand sprinkled on circular plates of mica. The second way was by the use of the Kundt dust figures in glass tubes. He arrived at a value of 20,000 vibrations per second for the upper limit.

The next great advance in this field was made during the first World War and involves a completely new principle. It is the discovery of the piezoelectric effect.

B. Piezoelectric Effect

1. Early Investigations

Probably the first indication that a crystal would, under certain conditions, become charged, was many years ago when the Dutch settled in Ceylon. They observed the natives playing with crystal tourmaline that had been thrown in the fire and noticed that ashes clung to the crystal. This fact first became known in Europe about 1703, when the tourmaline was brought from Ceylon by Dutch merchants. In 1756 Aepinus established the electrical character when he noted the opposite polarities at the two ends of a heated tourmaline crystal. The term "pyroelectricity" was introduced by Brewer in 1824 after observing the effect with various kinds of crystals. Lord Kelvin was the first to state a definite theory of pyroelectricity, and he postulated a state of permanent polarization in every pyroelectric crystal. According to this theory, the pyroelectric effect is simply a manifestation of the temperature coefficient of this polarization.

Haurz, and later Becqurel, performed experiments on the compression of crystals. Becqurel, in a report dated 1828, described experiments in which mechanical stress had been applied to quartz and other crystals to produce charge. However, their results indicate that the charges that they measured were not due to mechanical strain, but to contact friction, since some of the crystals they measured are now definitely known to be not piezoelectric.

To Pierre and Jacques Curie is confidently given credit for the discovery of the piezoelectric effect in 1880. They were the first to discover the real pressure-electric effect, and thereby introduce an entirely new concept of the interrelations of mechanical and electrical energy. They found that certain crystals alter their linear dimensions when placed in an electric field; and that when subjected to mechanical pressure, the crystal develops electric charges on its surface, this latter effect having been predicted by Lippman shortly after the first discovery. Their discovery was not by chance. From previous study of the relation between pyroelectric phenomena and crystal symmetry, they were led to look not only for electrification from pressure, but also to foresee in what direction pressure should be applied, and in which crystal classes the effect was to be expected.

2. Properties of Quartz

There are a large number of crystalline substances which do exhibit piezoelectric properties, but quartz is the only material which is truly satisfactory for frequency control purposes. Rochelle salts exhibit the most intense piezoelectric properties, but are unsuitable because they are too unstable both physically and electrically.

Quartz is silicon dioxide (silica) and is found throughout the world in many different forms. It occurs most commonly in the sands and sandstones of the earth, and occurs in rocks of igneous origin, such as granite. It has many commercial applications, and is used in the manufacture of piezoelectric devices, lenses, balance weights, chemical ware, and abrasives. Because of its extremely low internal friction and small thermal expansion coefficient, it is highly valued for suspensions in scientific apparatus.

Quartz is an exceptionally hard material, having a rating of 7 in Moh's Scale of Hardness, where the diamond is rated at 10. It is very stable, both physically and chemically; it is not affected by common acids and can be fused only with great difficulty. For piezoelectric applications, comparatively large natural crystals of high purity are required. Brazil, at present, has the only suitable supply of natural crystals.

3. Definitions

The theory of piezoelectricity is based on thermodynamic principles enunciated by Lord Kelvin. His many applications of thermodynamics to crystals marked a great advance in the study of crystal physics. In 1910 Woldemar Voigt published his "Lehrbuch der Kristallphysik" which has ever since been the Bible for workers in the field.

Piezoelectricity may be precisely defined as "electric polarization produced by mechanical strain in crystals belonging to certain classes, the polarization being proportional to the strain and changing sign with it." This is a definition of the direct piezoelectric effect. It is also a reversible phenomena. The inverse effect is the converse of the direct effect and results in a deformation of the crystal when electrically polarized, by an amount proportional to the polarizing field.

Pyroelectricity may be defined as a state of electric polarity produced on certain crystals by a change of temperature.

The question of the relation of pyroelectricity to piezoelectricity has been much discussed, as the two effects are closely related. Voigt pointed out that a distinction must be made between "true" pyroelectricity caused by a change in temperature alone and the "false" pyroelectricity that is due to the deformation which accompanies a change in temperature and which is therefore of piezoelectric origin.

X-ray studies of crystals indicate that the orderly groupings of their atoms and the distances between the atoms in a crystal have been quite accurately determined because of their precise alignments. The piezoelectric effect, or pressure effect, is derived from the fact that the arrangements of the atoms and their accompanying charges in quartz happens to be such that mechanical force and motion change the positions of the centers of "positiveness" and "negativeness", and the crystal acquires an electrified condition, evidence that energy has been transformed.

There are thirty-two different classes of crystals, and they are arranged in order of the ascending symmetry of their molecules. Twenty of the classes are piezoelectric, and twelve are not. A body or any one of its physical properties may be symmetrical with respect to a point, a line, a plane, or any combination of these. If symmetrical with respect to a point, the body is "centrosymmetrical" and can possess no polar properties. Therefore, no piezoelectric crystals are found in any of the eleven centrosymmetrical classes. With one exception, all classes which do not have a center of symmetry are piezoelectric.

Piezoelectricity remained a laboratory curiosity for almost a third of a century after its discovery. Under the spur of wartime activity in 1917, Langevin of Paris conceived the idea of exciting quartz plates as emitters and receivers of high frequency sound waves under water for the detection of submarines. The method was not actually used during the war because it was not completed until later, but it has become a valuable method of locating immersed objects and of exploring the ocean bottom.

III. QUARTZ CRYSTALS AS FREQUENCY STABILIZERS IN RADIO FREQUENCY CIRCUITS

A. Cady's Contribution

In 1918 W. G. Cady was led to examine certain peculiarities in the electrical behavior of Rochelle salt crystal plates around the frequencies of mechanical resonance. Out of this experience came the development of the piezoelectric resonator and its various uses as stabilizer, oscillator, and filter, for which quartz was found to be the most suitable material. The use of quartz crystal plates as stabilizers of electrical vibrations proved to be of enormous importance in the development of radio broadcasting. Cady applied Voigt's fundamental piezoelectric relations to the case of a vibrating crystal and derived the equations giving the reaction of the crystal upon the driving circuit. Quoting from his paper which he presented before the American Physical Society of 1921, he clearly sets forth the method by which stabilization occurs, as follows:

> A plate properly cut from a piezoelectric crystal and provided with metallic coatings vibrates mechanically when the coatings are connected to an E.M.F. of high frequency, provided that the frequency is sufficiently near the natural frequency of mechanical vibration. The absorption of energy gives the plate an effective series resistance which is a maximum at the resonant frequency. The effective parallel capacity of the plate is a maximum at a frequency slightly below resonance, passing through the normal value at resonance. The total range in capacity is greater, the less the vibrations are damped, and in the case of quartz, it may be more than twenty times as great as the normal capacity of the plate. The accompanying change in frequency may be a very small fraction of a percent.

> This dependence of capacity upon frequency may be utilized as a frequency stabilizer, by simply connecting the piezoelectric plate in parallel with the tuning condenser of an ordinary vacuum tube oscillating circuit. When the frequency is slightly above that at which the plate is in mechanical resonance, an increase in the capacity of the variable condenser is accompanied by a nearly equal decrease in the effective capacity of the plate, so that the frequency remains constant within exceedingly narrow limits. If the condenser reading is increased beyond an amount corresponding to the maximum plate capacity, the plate suddenly stops vibrating, and the frequency abruptly decreases by a large amount. A similar process, in the reverse sense, takes place on decreasing the capacity of the variable condenser.
>
> For example, a certain quartz plate 3.9 cm. long vibrated at a frequency of about 69,700. A change in the variable condenser which, when the quartz plate was removed, altered the frequency by three percent, varied it by less than one part in twenty thousand when the quartz was in the circuit. This plate had coatings so small that its normal capacity was only about 0.67 micro-micro-forads; yet when vibrating, its effective capacity varied from 10 to -9 MMF.[1]

The explanation of the apparent negative capacitance was given independently by Van Dyke in 1925 and by Dye in 1926, both of whom showed that the vibrating crystal is equivalent to an electrical system consisting of an inductance, capacitance and reactance in series, which is in parallel with the electrostatic capacitance of the crystal. When the frequency is above that at resonance, the system is inductive, and acts as a negative capacitance in series with a resistance.

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[1] Robert W. Woods, The Science of Inaudible Sounds, p. 37.

B. Properties of Quartz Plates and the Equivalent Electrical Circuit of the Oscillating Quartz Crystal

In order to take advantage of the piezoelectric effect of quartz, small plates are cut from the raw natural crystal. These plates must be cut in certain definite directions with respect to the axes of the raw crystals; they must be free from mechanical and electrical flaws; and each must be carefully ground such that its major faces are essentially plane and parallel. When one of these plates is placed in an oscillating electric field, it will vibrate mechanically and produce a counter-voltage at the frequency of the applied field. The magnitude of this vibration will be quite small; but if the frequency of the applied field is adjusted to the natural vibrating period of the plate, the vibrations will become vigorous and have an appreciable amplitude. If the field is sufficiently great, the vibrations may easily become so strong as to physically rupture the plate.

A plate, when distorted by physical force, will develop an electric charge. If it is X-cut (the planes of its faces perpendicular to the direction of one of the side faces of the natural crystal and parallel to the axis of the crystal along its length) and the force is normal to the major faces, the charge developed will be approximately 6.36 x 10 -8 esu/dyne.[2]

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[2] *Frequency Control with Quartz Crystals*, Engineering Bulletin E-6, Bliley Electric Company, p. 2

This charge will be independent of crystal face area or thickness and of temperature for any value up to 550° C. At 573° C. piezoelectric action ceases. For pressure measurement purposes, the amount of charge, or the voltage resulting from the charge, can be determined from the relation ($Q = CE$) where C is the circuit capacity.

For best results, it is important that the quartz plate be entirely free from mechanical or electrical flaws. If flaws are present, the crystal cannot vibrate freely, and, therefore, it may oscillate weakly or not at all.

The types of flaws which appear in the raw quartz are bubbles, needles, veils, strains, fractures, phantoms, and twinning. Bubbles are a physical defect in the quartz material and appear in different sizes and formations. Veils and needles are small bubbles and striations which occur in groups. Strains are permanent internal stresses which cannot be relieved. Fractures are definite cracks caused during formation of the crystals or by physical breakage during mining and handling. Phantoms are a variation in cross sectional appearance of the crystal such that one crystal appears to have grown inside another, probably a change in growth of the crystal during formation. Twins are the result of one crystal growing within another, either totally or partially. In order to prevent the appearance of these flaws in the crystal, it is necessary to carefully select the raw quartz and then use only the sound portions.

The greatest practical value of quartz crystals is derived from the fact that they can be produced as mechanical vibrators having electrical characteristics not fully attainable by any ordinary electrical circuit or component. In radio-frequency oscillatory systems, the quartz crystal is by far the best form of frequency stabilizer available. In filter circuits, where it is desired to pass only a relatively narrow band of frequencies, great simplification and better results can be obtained through the use of quartz crystals.

The electrical action of an oscillating quartz crystal may be analyzed by reference to its equivalent electrical network as shown in Fig. 1. This equivalent network can be used to exactly define the electrical behavior of a crystal, and it provides the basis for mathematically designing certain type crystals. The inductance, L, represents the mass of the crystal, the capacity, C, the resilience, and the resistance, R, the frictional losses. C_1 is the capacity due to the crystal electrodes with the crystal as the dielectric, while C_2 represents the series capacity between the crystal and its electrodes.

Neglecting C_2, it can be seen that the equivalent electrical network composed of L, C, R, C_1 has the properties of either a series or a parallel resonant circuit. At some definite frequency where L and C are numerically equal, the requirement is fulfilled for a series resonant circuit. The frequency at which this occurs is called the series resonant

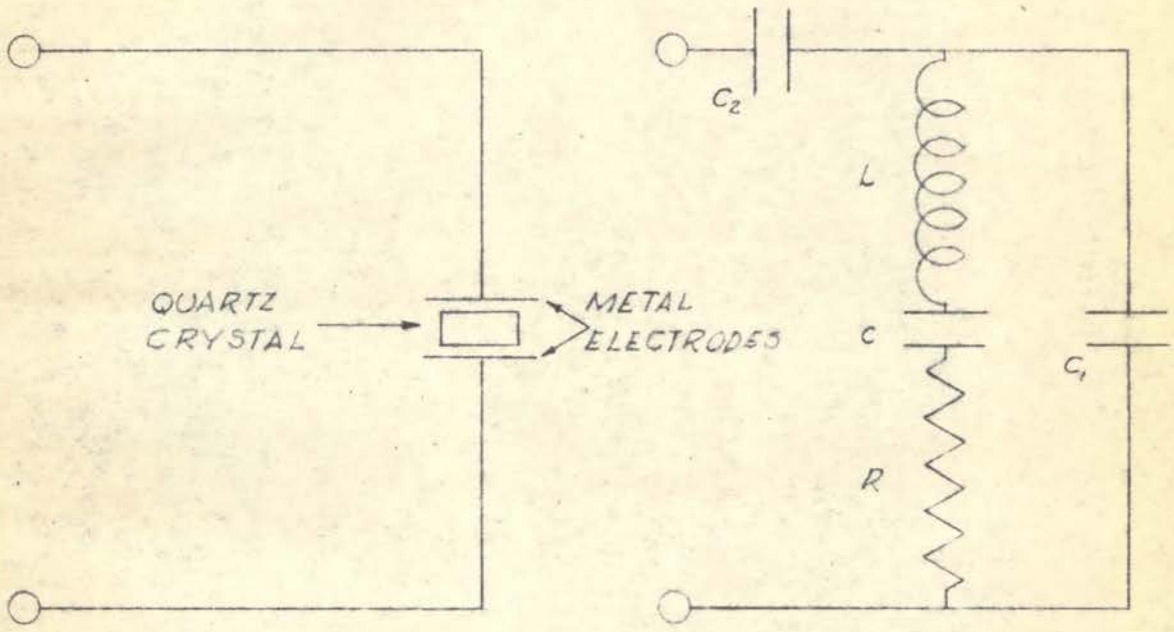

FIG. 1

or natural frequency of the crystal. At a somewhat higher frequency, the effective reactance of L and C will be inductive and numerically equal to the reactance of C_1. At this frequency anti-resonance occurs and the crystal acts as a parallel or anti-resonant circuit. The capacitance C_2 is effective only when the crystal electrodes are not in very close contact with the crystal faces. As the value of C_2 is decreased, the resonant frequency will increase.

Quartz crystals have very high Q factors ($Q = 2\pi f\ L \div R$). Commercially produced crystals have Q factors ranging from about 6,000 to about 30,000 while in the laboratory crystals with Q factors up to 400,000 have been reported.[3] The inductance of quartz crystals is very large and varies from 0.1 henry to 100 henries with individual crystals. It depends on the manner in which the crystal is cut from the raw quartz, its physical proportions, and the frequency.

In an oscillator circuit operating at radio frequencies, the frequency stability is to a great degree determined by the Q of the frequency determining tank circuit. Since the Q of quartz crystals is many times greater than that obtained from conventional inductance capacity tanks, it follows that crystal frequency control gives the greatest frequency stability. It may be noted, by way of explanation, that the oscillating frequency of a conventional oscillator circuit is that frequency

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[3] *Ibid.*, p. 3

at which the total circuit reactance reduces to zero. Any circuit changes such as aging of the tube, varying voltages, or others, cause the resonant frequency to change. When a crystal is used as a frequency stabilizer, any change in resonant frequency due to variations in circuit components tends to change the effective electrical characteristics of the crystal, namely, the capacitance or inductance, or both, so that the resulting circuit frequency remains the same, or almost the same, as before. Because quartz crystals have a very steep resonance curve, a large change in reactance can be brought about with only a small shift in frequency.

C. Crystals at Resonance

In oscillator circuits, employed for the majority of radio transmitter installations, the crystal operates in the same manner as a parallel, or anti-resonant electrical circuit. For this reason, quartz crystals used for frequency control of vacuum tube oscillators are usually calibrated at their anti-resonant frequencies.

When a crystal is placed in a vacuum tube oscillator circuit, the effective value of the capacity, C_1, changes. This change is due to several reasons. The value of C_1 will vary with different crystal holders and will be affected by the dynamic input impedence of the oscillator tube and the capacity added by connecting wires between the crystal and the tube.

The impedence in the plate circuit of the tube will also influence the dynamic impedence of the grid circuit to an extent dependent on operating conditions.[4]

When a quartz crystal is used for a specific application where frequency accuracy is very important, the possible change in frequency between its calibrated value and the final equipment must be considered. This is especially important where the allowable frequency tolerance is very small.

There are two methods of causing a change in the oscillating frequency of crystal operating at, or near, anti-resonance. Because of the fact that the parallel capacity will influence the frequency of a crystal, it is possible to include a variable frequency feature. One method is to connect a variable air condenser in parallel with the crystal in order to vary C_1. Increasing the capacity of the condenser will cause the frequency to be lowered; and if it is increased by a sufficient amount, it may effectively short out the crystal. For small ranges in frequency adjustment, however, the effect of the condenser will not be harmful. This method of shifting the frequency is generally applied to crystals higher than 2000 kc., but may be used at lower frequencies.

A variable air gap crystal holder gives the most convenient method for shifting frequency. One of the crystal electrodes may be raised or lowered over the crystal. This brings

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[4] *Ibid.*, p. 3

about a simultaneous change in the values of C_1 and C_2; the frequency increasing as the air gap is increased. The resulting decrease in oscillating properties is not serious for small frequency changes, and the only essential consideration is that the crystal be used in a circuit where the driving voltage does not reach high values. This is to prevent an arc being developed across the air gap which would cause erratic oscillation and possible damage to the crystal.

The impedence of a quartz crystal is lowest at the resonant frequency and highest at anti-resonance. At frequencies remote from these values, the crystal acts as a fixed condenser. The reactance curve of a quartz crystal is shown in Fig. 2. The property of a crystal to act as a resonant circuit, with a very rapid increase in impedence on either side of resonance, is very useful in radio frequency filters and for frequency control of certain types of oscillator arrangements. Quartz crystals operating at their resonant frequencies are used as frequency stabilizers in relaxation oscillators, which rely on the time constant of resistance-capacity networks. Such oscillators have a high harmonic output but are not very stable. They can be readily stabilized, however, by substituting a quartz crystal for one of the coupling condensers. Practical limitations in obtaining resistance-capacity combinations with a very short time constant limit circuits of this type to frequencies below 150 kc.

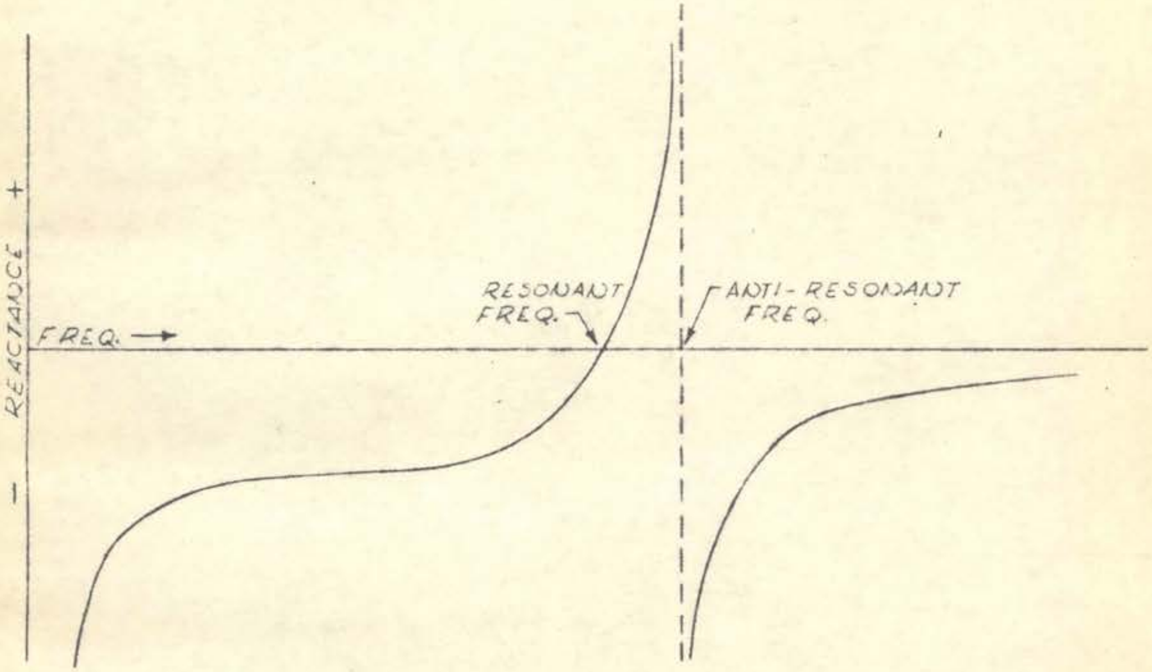

FIG. 2

The frequency of a crystal oscillating at resonance cannot be varied by means of a parallel condenser. It may be shifted, however, by causing a change in C_2. This may be accomplished by connecting either a variable air condenser or an inductance in series with the crystal. A decrease in frequency will result, if the inductance is increased, while if the condenser is decreased, the frequency will be increased. The possible amount of frequency adjustment is limited in that an increase of the series element reduces the voltage across the crystal (excitation), causing the circuit frequency stability to be lowered as the series impedence is increased.

D. Effects of Temperature

The frequency of a crystal is influenced to an appreciable extent by the temperature at which it is operated. The magnitude of this effect is determined by the way in which the crystal is cut from the natural quartz, the shape and size of the crystal, the precision of grinding, and the characteristics of the quartz itself. It is expressed as the number of cycles change per million cycles of frequency per degree Centigrade variation in temperature, and is termed the frequency-temperature coefficient. It may be positive or negative depending upon whether the frequency increases or decreases with increasing temperature.

The frequency temperature coefficients of quartz crystals vary with individual cuts from minus 25 to plus 100 cycles per megacycle per degree Centigrade.[5] With X-, C-, or E-cut crystals, the frequency at any temperature can be determined when the frequency-temperature coefficient and the crystal frequency at any other temperature is known. Such calculations are not possible with low frequency-temperature coefficient crystals because the curve of frequency versus temperature is not generally a straight line. The coefficient may be positive over one part of the temperature range and negative over other portions. The commercial practice with these crystals is to give the average frequency-temperature coefficient over a given range of temperature (generally 20° C. to 55° C.).

The temperature at which a given crystal oscillates depends on the ambient amount of heat developed by the crystal in oscillating, and the rate of heat dissipation by the crystal holder. It is essential, therefore, that for high frequency stability, a crystal holder having high heat dissipating abilities should be used, and also the intensity of vibration should be kept at the lowest possible value so as to keep the developed heat at a minimum.

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[5] _Ibid._, p. 7

IV. MODES OF VIBRATION OF QUARTZ PLATES

Any quartz crystal has two, and sometimes three, widely separated possible frequencies of oscillation. This is due to the fact that any body of this type may be made to vibrate in at least two different manners. Also, if the crystal faces are not sufficiently plane and parallel, the crystal may have one or two additional frequencies close to the thickness frequency, because it may oscillate at slightly different frequencies over small portions of the surface. At the present time, quartz crystals are produced in the full range from 16 kc. to 30,000 kc.

A description of the X- and Y-cut crystal will now be given, to be followed by several different modes of vibration. A perfect quartz crystal appears as indicated in Fig. 3. The longitudinal axis Z passes vertically through the center of the uncut crystal and is called the optical axis. Light passing along this axis travels with uniform velocity, but should it travel at some angle to the optic axis, is doubly refracted, resulting in two different velocities. The three axes, X_1, X_2, and X_3 which pass through the corners of the hexagon are termed the electrical axes, while those which are perpendicular to the crystal faces, labeled Y_1, Y_2, and Y_3 are designated the mechanical axes. The X-cut crystal has its face perpendicular to the X axis and its length parallel to the Y axis, and the Y-cut crystal has its face perpendicular to the X axis and its

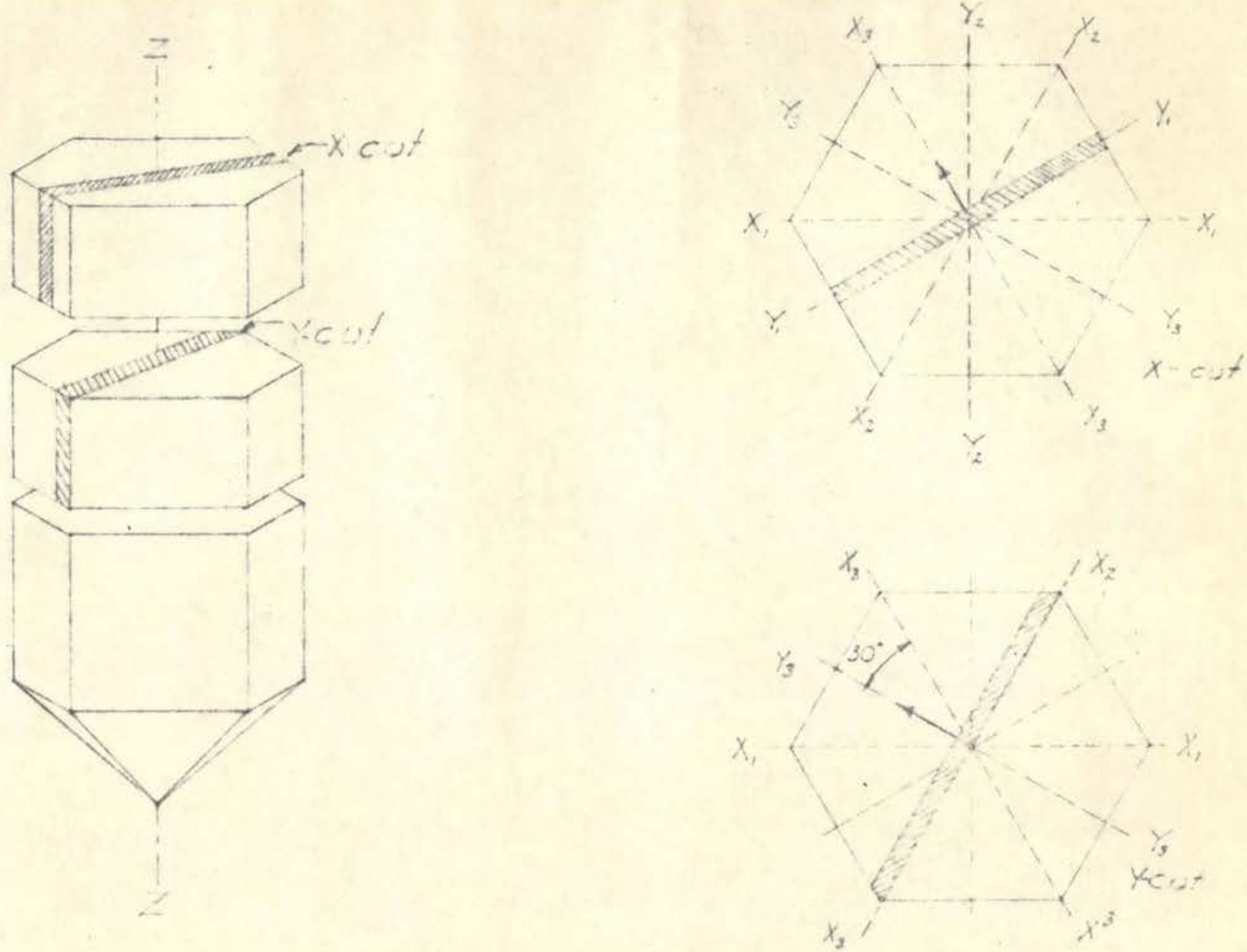
Z
X cut
Y cut
Z
X_3
Y_2
Y_2
Y_3
Y_1
X_1
X_1
Y_1
Y_3
X_2
Y_2
Y_3
X - cut
X_3
X_2
Y_3
30°
X_1
X_1
Y_3
Y cut
X_2
X_3

FIG. 3

length parallel to the Y axis. The three axes are mutually perpendicular and intersect at the center of the hexagonal cross section.

In Fig. 4 is shown a section of a quartz crystal perpendicular to the optic axis (the Z axis perpendicular to the plane of the paper). If the plate is subjected to a force producing compression parallel to the X axis, the face which has the largest X value (at left) will become negatively, and the opposite face positively, charged. Dilation in the X-direction reverses the charges. This is called the longitudinal effect. Dilation in the Y direction produces charges distributed as in the case of compression along X. This is called the transverse effect. Compression along Z, the optic axis, gives rise to no charge.

Conversely, if the surface having the largest X value is charged positively and the other negatively, the plate will expand in the X direction (reciprocal longitudinal effect) and contract in the Y direction (reciprocal transverse effect). Electric fields in the Y and Z direction produce no deformation. The magnitude of the amplitude of the deformation with an alternating electric field, when resonance occurs, may be one thousand times greater than with a static field of equal value. Meisner showed that, since the modulus of elasticity of quartz is not uniform in all directions in the YZ plane, but a minimum value at +71°, a circular disc cut from the plate will have three natural frequencies of vibration, one parallel

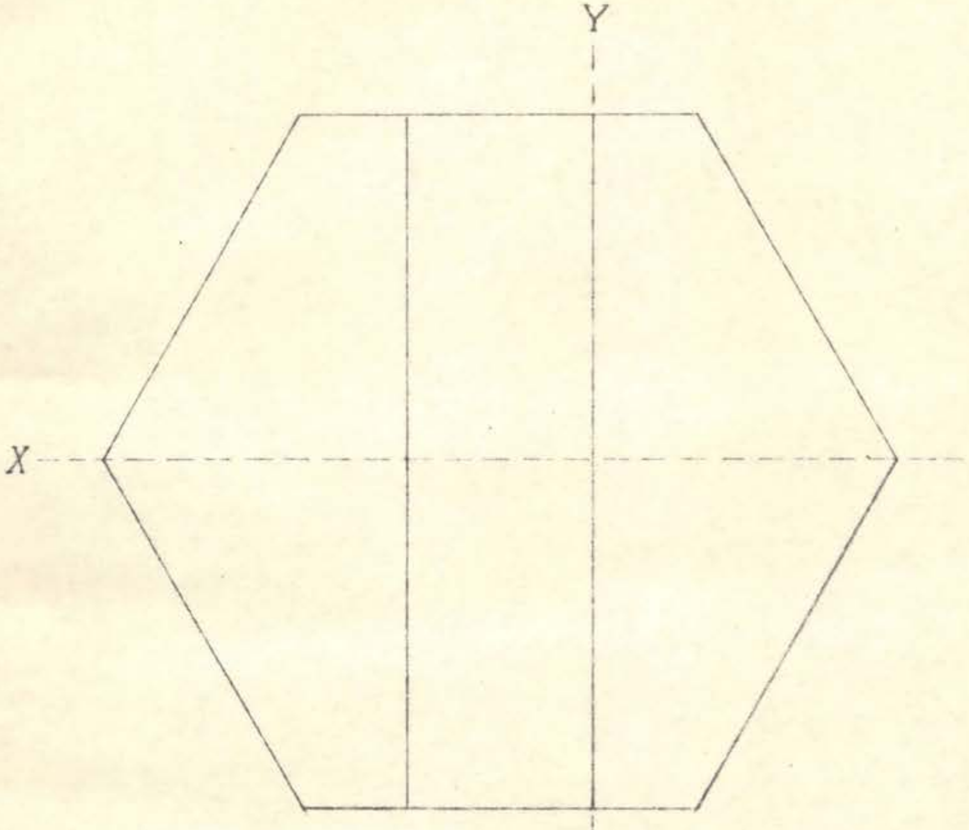

FIG. 4

to the X axis and the other two parallel to the inclined directions just mentioned.[6] On this account plates or rods cut with their faces parallel to X, Y, Z bend when vibrations along the Y axis are excited, and a circular disc will not vibrate with an equal amplitude over its entire surface, and will break into fragments if too high a potential is employed.

X-cut crystals oscillate through the thickness at a frequency largely determined by that dimension, and they have a negative frequency-temperature coefficient which ranges from 20 to 25 cycles per megacycle per degree Centigrade. They can be manufactured in the frequency range from 250 kc. to about 10,000 kc.

In the lower range of radio frequencies from 16 kc. to 250 kc., the physical dimensions of X-cut crystals and other plate type crystals become too great to be practical. To reduce the crystal size, they are cut as "bars" where one dimension is considerably greater than the other two. Such crystals oscillate along the greatest dimension and their oscillating frequency is largely determined by that dimension. X-cut bars have a negative frequency-temperature coefficient which ranges from 4 to 15 cycles per megacycle per degree Centigrade.

Y-cut crystals oscillate in shear and can be made in the frequency range from 200 kc. to about 8,000 kc. Shear vibration

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[6] Woods, op. cit., p. 44.

is illustrated by Fig. 5. The frequency-temperature coefficient of Y-cut crystals is positive and may vary from 60 to 100 cycles per megacycle per degree Centigrade. Because of this high frequency change with temperature and also the fact that the crystals will suddenly change frequency at various points over a wide temperature range, the use of Y-cut crystals has been discontinued in favor of other types.

In the frequency range from 85 kc. to 10,000 kc., both X- and Y-cut crystals have been almost altogether superseded by low frequency-temperature coefficient crystals. These crystals, which oscillate in shear, afford excellent frequency stability under varying temperature conditions.

The Bliley C- and E-cut crystals which are harmonic type crystals and are used in the frequency range from 11,000 kc. to 30,000 kc. C-cut crystals, having a frequency-temperature coefficient of plus 20 cycles per megacycle per degree Centigrade cover the frequency range from 11,000 kc. to 23,000 kc. E-cut crystals, which have a frequency-temperature coefficient of plus 43 cycles per megacycle per degree Centigrade are used from 23,000 kc. to 30,000 kc.[7]

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[7] Frequency Control with Quartz Crystals, p. 8.

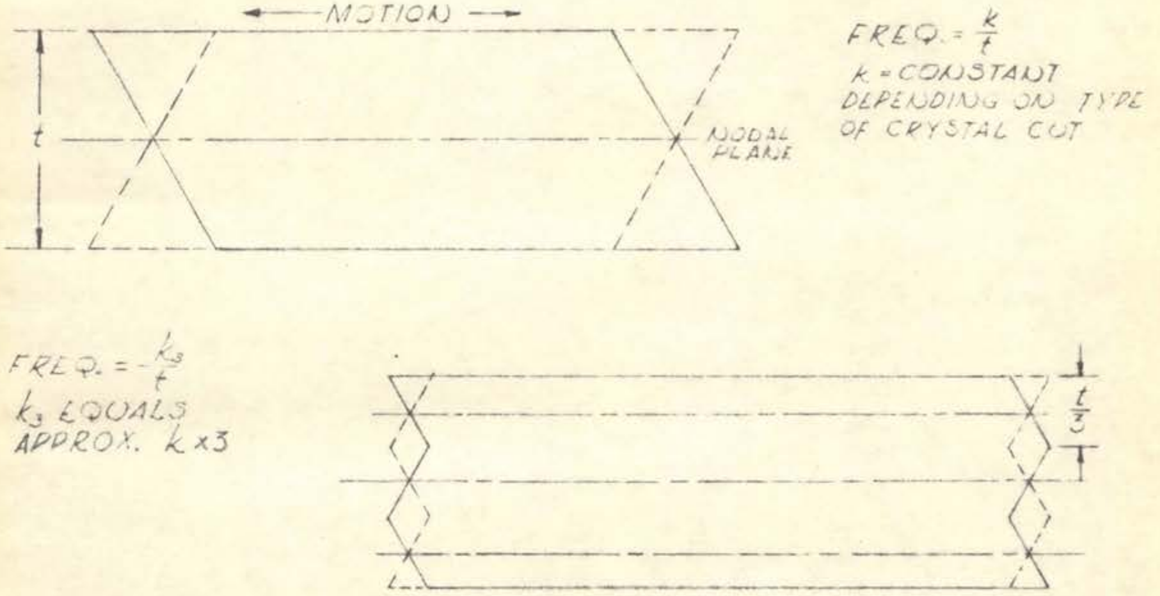
MOTION
t
NODAL PLANE
FREQ. = $\frac{k}{t}$
k = CONSTANT DEPENDING ON TYPE OF CRYSTAL CUT
FREQ. = $\frac{k_3}{t}$
k_3 EQUALS APPROX. k x3
$\frac{t}{3}$

FIG. 5

V. EXPERIMENTAL WORK

A. Construction of a Supersonic Generator

A Bliley 100 kc. quartz crystal was connected into an oscillator circuit and caused to vibrate at its natural frequency. The crystal was enclosed in a metal container which had two terminal points. The circuit that was used is illustrated by Fig. 6. The tank circuit consisted of the variable condenser which had an approximate range of 50 MMF to 500 MMF and a coil that had an approximate value of 13 milli-henrys. The tube used was a U x 201A that operated with a filament potential of 6 volts at .25 ampere. The filament current was kept constant by means of the variable resistor and was indicated by the d.c. ammeter. A negative bias of 4 volts was connected in series with 47,000 ohms to the grid of the tube. In order to maintain oscillations, it was necessary to use a variable feedback condenser between the plate and the grid with a range of from 45 MMF to 390 MMF. The plate potential was 90 volts d.c., and one condenser of .59 MF was connected across the "B" battery and another of 1000 MMF across the negative bias to by-pass the high frequency.

The crystal began oscillating when the tank was an inductive reactive circuit; and as the capacitance was increased, the oscillations became much stronger until a point was reached where the tank circuit became capacative and the oscillations stopped. The d.c. ammeter in the plate circuit indicated when

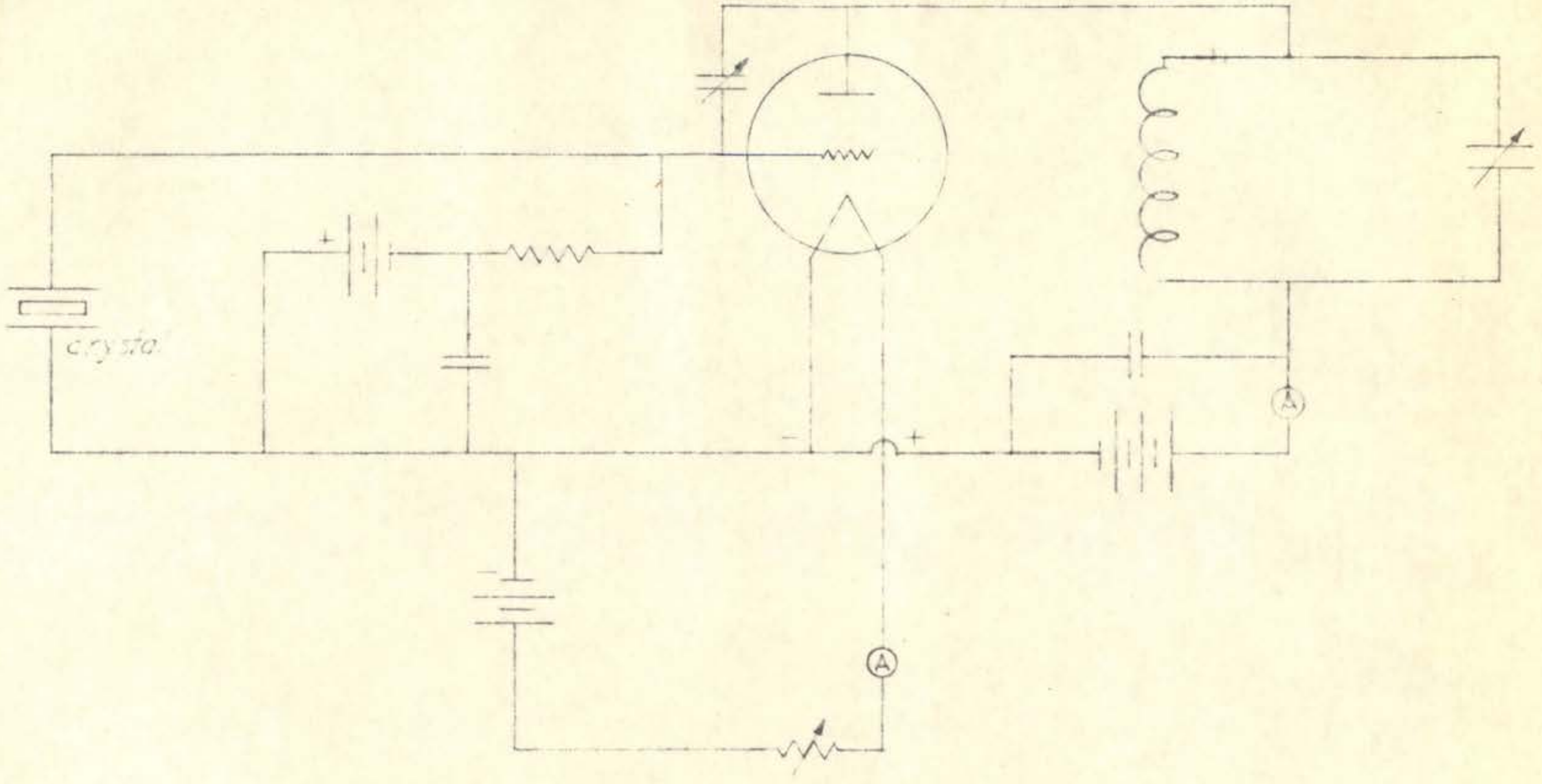

FIG. 6

the crystal was oscillating. When oscillations did not take place, it indicated a maximum value which decreased as oscillations began. The variable feedback condenser between the plate and the grid of the tube was necessary to maintain the oscillations, and the position at which it was used gave an approximate value of 45 MMF. An analyzer was also employed to determine the frequency of the oscillations, and it was interesting to note that the crystal was definitely controlling the frequency of the circuit because on shifting the tank condenser even by large amounts, the frequency varied little from the 100 kc. at which it was calibrated. All of the harmonics of the natural resonant frequency of the crystal could also be readily found by the analyzer.

A second quartz crystal of a natural vibration frequency of 400 kc. was next used as a source of supersonic waves. This crystal was a round flat plate about 3 centimeters in diameter and ½ centimeter thick. It was not enclosed in a metal container but had the flat surfaces coated with an insulating material. Two brass rings whose outer radii were equal to that of the crystal and about one-sixteenth inch thick were used as electrodes, and the crystal set between them. The oscillating circuit was identical to that used with the previous crystal with the exception that a coil of approximately 4 milli-henry inductance was used in the tank circuit. The same variable tank condenser was used as before. The oscillations again did not start until there was feedback capacitance between the plate and the grid of the tube, this amount being approximately the same as before. The signal came in very strong; and as in the previous case, the crystal very readily stabilized the frequency of the oscillator circuit, and the various harmonies were easily detected with the analyzer.

B. Assembly and Operation of the Model U-300 Ultrason

Televiso Products has developed a supersonic generator designated Model U-300 which can be used either for research, where high power is requisite, or for specific production applications.

Figure No. 7 illustrates the basic circuit of the U-300 Ultrason. T_1 is the oscillator tube; VC is the vernier capacitor for panel control of vibration frequency; L_1 is the main inductance; L_2 is the step-up transformer; X is the piezo-quartz crystal which is contacted on each facing by the crystal holders CH; R_1 is the vibration intensity control which permits a continuous adjustment of vibration voltage across the crystal.[8]

The Model U-300 Ultrason operates on a 115-volt, 50-60 cycle line and produces a maximum of 250 acoustical watts in an oil bath. The vibration frequency control varies the vibration frequency from 420 to 500 kc. which permits comprehensive

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[8] "Televiso Products Co., Bulletin No. 37", p. 3.

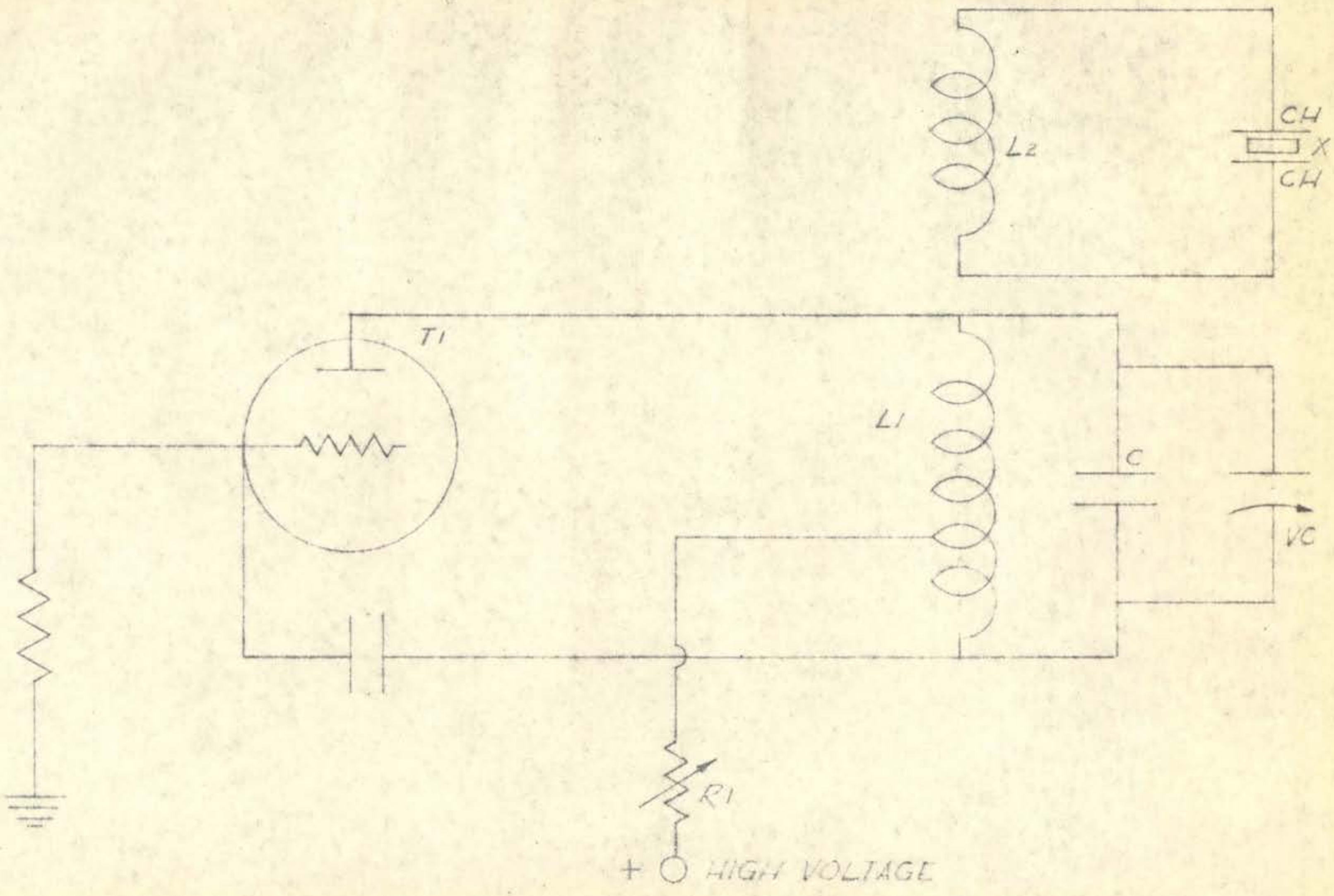

FIG. 7

investigations of most problems and applications. At mechanical and electrical resonance, it is possible to raise a fountain of oil to a height of twelve inches or more. The vibration intensity control varies the power at the crystal and is measured by a 0-5000 d.c. voltmeter and a 0-500 ma plate current meter.

When the U-300 is being used over extended periods of time, it is necessary to cool the oil surrounding the crystal to ambient temperature. This is accomplished by a cooling unit which is a simple pumping and filtering system. The type of oil used for cooling is important. For proper vibrating conditions, transformer oil having a low viscosity and a high insulating factor is essential.

The crystal is mounted between two brass cylinders and is positioned by lucite spacers. The insulating medium surrounding the crystal is type U-300 Vibrol. To reduce arc-over inside the crystal holder, all insulating surfaces are constructed of lucite.

The U-300 Ultrason was assembled upon its arrival and a few tests run. In order for the generator to function properly, it is important that the crystal, crystal holder, and surrounding positions to be well cleaned.

High frequency sound waves have many applications in industry and also in research. The formation of stable emulsions and the solubility of compounds resulting from ultrasonic action is being examined by organic chemical companies. Immiscible liquids, such as oil and water and oil and mercury, were transformed into stable emulsions by treatment with this machine. Also very fine dispersions of mercury, sulphur, and silver were produced in water.

Ultrasonic waves not only have a dispersive power but also a shattering effect. Depolymerization by ultrasonics is still a doubtful subject although highly polymerized molecules can be split up at around 700 kc. The depolymerization of formoldehyde with this machine was attempted but was not successful.

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