

also been recorded in Fig. 7. In Fig. 4 are given curves for the separation, the velocity of separation, and the acceleration of separation of the contacts in our relay as determined by the arrangement described in this paper.

In Figs. 5, 6, and 7, are shown superimposed opening and transient discharge records. In all the figures showing transients, each division along the x -axis represents 3 milliseconds; each division on the y -axis corresponds to 285 volts. The glow discharge, called "type A" by Curtis,¹ and "plateau" by Martin and Stauss,² is shown in Fig. 5. It is seen to begin, when present, in the earliest stages of contact separation when the gap is

very small. In Figs. 6 and 7 are shown the relaxation discharge called "type B" by Curtis and "strikeover" by Martin and Stauss. These, if present, can occur either early or late in contact separation. An arc is also shown in Fig. 7, occurring before the strikeover. The damped oscillation which Martin and Stauss found to terminate most discharges is present in Figs. 5-7.

The method described here can also be used to exhibit contact bounce on closing contact points. The method is expected to be useful in studying delays in contact opening caused by welding, because accurate separation measurements will be possible.

Design of Variable Resonant Frequency Crystal Transducers

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Design considerations involved in the development of low loss continuously variable resonant frequency crystal transducers are discussed. A description of such a system employing liquid mercury as a backing of continuously variable dimensions is presented. The important aspects; tight coupling of the crystal and mercury backing, and decoupling of the crystal and mercury from the supporting structure are considered in detail. Construction procedure on a unit to cover the frequency range 40 to 80 kc is indicated. Experimental results on the magnitude of the electrical input impedance as a function of frequency and mercury column length are given. A comparison of the variable resonant frequency unit used as a transducer with a series of fixed resonant frequency transducers is presented.

I. INTRODUCTION

IN this paper we are concerned with experimental problems associated with realizing a low loss crystal system capable of continuous and wide variation in the resonant frequency. The detailed design of a system to operate in the frequency range below 200 kc is presented. Some previous work on variable resonant frequency crystal systems has been reported in the literature by Fox and Rock.¹

II. DESIGN CONSIDERATIONS

In the frequency range 20 to 150 kc it is convenient to use a piezoelectric element vibrating in a longitudinal mode to obtain resonant operation with high electric field strength at reasonable voltages. A $45^\circ Z$ cut crystal of ammonium dihydrogen phosphate is thus an appropriate piezoelectric element. Figure 1 illustrates a crystal cut of this type. The first resonant frequency is approximately inversely proportional to the length of the cut crystal. The resonant frequency for a specific size will serve to illustrate the order of magnitude of the quantities involved. For example, a cut crystal $\frac{5}{8}$ in. long and $\frac{1}{2} \times \frac{5}{8}$ in. in cross-section dimensions has a fundamental resonant frequency of about 80 kc. Since the radiating face of the crystal may be small, especially if

high electric field strengths are desired without excessive voltages, the total power radiated as acoustic energy may also be relatively small. If high power output is desired, the radiating face of the transducer can be increased by arranging the requisite number of crystals in parallel.

When the crystal is tightly coupled to a solid backing material, the resonant frequency of the composite system is, in general, shifted from that of the crystal alone. Figure 2 shows calculated values of the resonant frequencies of composite systems consisting of a 2.0 cm $45^\circ Z$ cut bar of ADP cemented to various lengths of different backing materials. These curves are calculated on the basis of a one-dimensional theory for both the crystal and the backing material. A relatively low loss

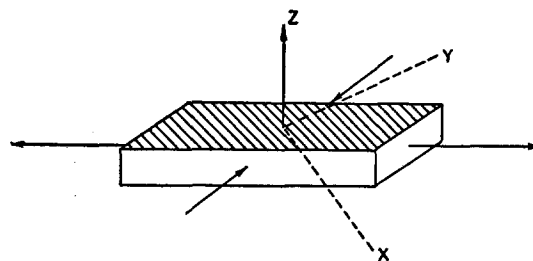


Fig. 1. $45^\circ Z$ cut ADP crystal. The cross-hatched areas indicate the electroded surfaces.

¹ F. E. Fox and G. D. Rock, Proc. Inst. Radio Engrs. 30, 29 (1942).

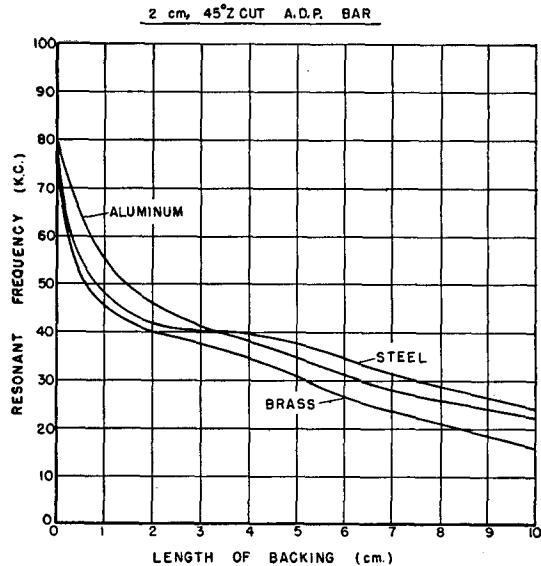


FIG. 2. Resonant frequency versus length of backing material for various crystal-metal composite systems.

system can be obtained if materials of low internal loss are used for backing and for coupling and if the interfaces are free of gaseous inclusions.

In order to realize a practical system which is capable of continuous variation in resonant frequency and which is relatively low loss, it appears necessary to satisfy the following requirements: (1) Size or shape continuously variable; (2) tight coupling at interfaces; (3) low loss components; (4) defect-free interfaces; (5) decoupling from supports; (6) absence of large discontinuities in characteristic acoustic impedance between crystal and backing materials.

The first two requirements are necessary in order that a wide variation in resonant frequency is possible. The third and fourth are required in order to realize a low loss system, and the fifth eliminates unwanted modes of vibration and reduces loss; the sixth insures relatively uniform variation of frequency and good energy transfer.

It should be pointed out that all of the above requirements except (1) are common to fixed resonant frequency systems; however, as a result of the increased complexity of variable resonant frequency crystal systems, the remaining conditions are more difficult to satisfy.

In the present investigation, the above conditions have been fulfilled by the design shown in Fig. 3. The ADP unit consisting of one or more crystals in parallel is supported, as illustrated, with provisions for coupling the mercury column and liquid medium to the ends of the unit. Continuous variation in size and shape of the resonator system is realized through a mercury column of variable length. This is accomplished by means of the piston arrangement indicated on the right. For this application, mercury has several advantages over many

other liquids. The characteristic acoustic impedance is $1.98(10)^6$ g/cm² sec as compared to a rough average of $1.0(10)^5$ g/cm² sec for most liquids. This means that the change in characteristic impedance in passing from a crystal or a solid metal to the liquid column is not great. In addition, its acoustic absorption coefficient is relatively low. Mercury is also desirable because an extremely short and complete column can be obtained. Films 0.001 in. thick are possible with the experimental arrangement shown in Fig. 3. This is of importance since a backing film which gave only partial coverage would result in undesirable unsymmetrical loading of the crystal or crystals.

Coupling the mercury to the crystal poses several problems. One difficulty is that it does not wet ammonium dihydrogen phosphate crystals; however, this can be surmounted by bonding a material to the crystal which will amalgamate with the mercury. This insures a tight coupling at this interface.

Many materials that form amalgams with mercury do so too rapidly for use in this application and the metal is either dissolved away, or deteriorated by fringing. It may also combine with the mercury to form undesirable solid alloys. A further condition imposed on the mercury-metal joint is that the mercury be restricted to the surface of the metal in direct contact with the mercury pool. Any spreading of the amalgamation to the crystal-metal interface cannot be tolerated. This difficulty is eliminated by depositing a nickel plate on the surface of the metal where amalgamation is not desired. This technique is highly satisfactory; the nickel completely prevents the creep of the mercury over the alloy.

Various metals that will amalgamate with mercury were studied before an alloy having the necessary characteristics was obtained. One particular type of brass was found acceptable in many tests; however, the inability to reproduce identical specimens of this brass as tested by the action with mercury caused the rejection of all copper base alloys. These alloys contain zinc and tin which form objectionable films on the mercury surface. The formation of such films can be correlated with high acoustic losses in the system. Experimental results indicate that when contamination appears on the surface of the mercury, the quality factor of the composite system is low.* This implies that contamination may be present at the metal-mercury interface. The characteristics of the best brass were: composition 34 percent Zn, 60 percent Cu, 6 percent Pb and trace Sn, predominantly β -phase, small grain size, and a Rockwell hardness of the order of 85B. The limiting condition on increasing the hardness of the brass was the amount of reduction the alloy would sustain without rupture. Minute flaws in the specimen were particularly objectionable because of the increased rate of amalgamation in these regions.

Among other alloys considered were 24-carat gold and

* Quality factor is defined as the ratio of the electrical impedance at antiresonance to the impedance at resonance.

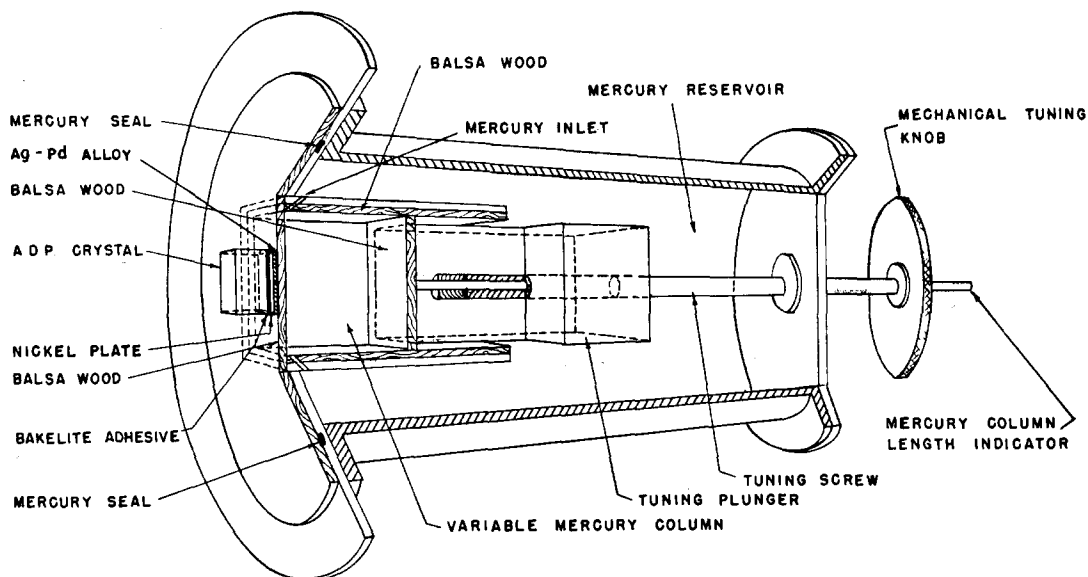


Fig. 3. Detailed diagram of a variable resonant frequency crystal system.

pure silver. These metals produce no surface contamination; however, units employing them had a lifetime of, at most, one day. The short lifetime is the result of rapid dissolving of gold and silver in the mercury. Mercury saturated with gold did not eliminate fringing of the plates. In addition, these pure metals form undesirable solid amalgams with the mercury. Another possibility considered was an alloy of gold or silver in which the alloying agent does not amalgamate. Experience with gold-platinum alloys showed that a non-amalgamating metal present in large amounts is not a sufficient criterion. A solid deposit formed on the surface of the metal when subjected to mercury, and the alloy became extremely brittle. This difficulty was attributed to the heterogeneous condition of the gold-platinum alloys. The heterogeneous domain probably extends from about 3 to 85 percent gold for Au-Pt alloys.²

It appears desirable, perhaps necessary, in this particular application that the alloy form a solid solution with no other phases present. A silver-palladium alloy of composition 60 percent Ag and 40 percent Pd satisfied our requirements. The composition is not critical. It is thought that the palladium-silver system is a simple solid solution free from transformations in the solid state for high percentages of both constituents.² Amalgamation is impeded and there is no evidence of contamination. The alloy is wettable and can be produced in flat sheets 0.002 in. thick. Tests are in progress to determine the lifetime to observable deterioration of a sample of such Ag-Pd alloy in contact with mercury originally free of silver. After ten months, there is no observable change in the alloy.

A second problem that arises in coupling together the mercury-crystal composite system is that associated

with the interface between the Ag-Pd alloy and the crystal. To establish a low loss system possessing variable resonant frequency characteristics, this bond must be free from all defects, such as gaseous inclusions. Tenacity is important if the system is to be rigidly coupled together. Low acoustic loss is also required. A polyester resin[†] was found satisfactory as a bonding material between the crystal and the alloy. The resin is applied as a monomer to the components to be bonded together. When benzoyl peroxide is used as a catalyst, the resin polymerizes as the temperature is raised. The time required for polymerization is a function of the temperature and the amount of catalyst added. Relatively low temperatures are used so that the crystal is not stressed much after return to room temperature as the result of the different coefficients of thermal expansion of the crystal and the Ag-Pd alloy.

The pressure required for bonding is slight, and in this application the weight of the crystal is adequate. Since no solvent evaporates from the resin during polymerization, shrinkage of the bond is minimized and layers free of defects and voids are possible. The bond thickness in the sketch of Fig. 3 is exaggerated, for illustrative purposes, as this layer rarely exceeds 0.001 in.

It is necessary to decouple the vibrating system from the supports to eliminate loss of energy through these members. We require here a material which has a very low acoustic input impedance, is not too readily deformed, is capable of fairly accurate dimensioning, and which will not contaminate the mercury. Cork and balsa wood were tested as decoupling materials. Balsa wood proved to be the more desirable because it is less porous than cork and can be held to more accurate dimensions. Contamination of the mercury as the result of deteriora-

² E. M. Wise, *The Platinum Metals and Their Alloys* (International Nickel Company, New York, 1941).

[†] BRS 16631 manufactured by the Bakelite Corporation of America.

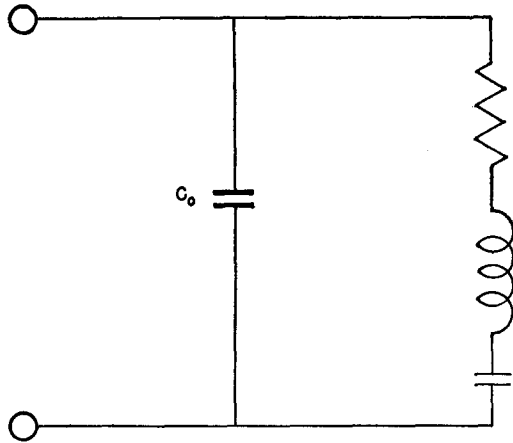


FIG. 4. Equivalent electrical circuit of a crystal vibrating near a resonant frequency.

tion of the decoupling surface is not as noticeable when balsa wood is employed. The present design utilizes this material throughout for decoupling purposes.

Continuous variation in size and shape of the composite mercury-crystal system is realized by the piston arrangement shown in Fig. 3. The length of the mercury column is variable from 0 to $1\frac{1}{2}$ in. The cross-section size is 2 by $2\frac{1}{2}$ in. The length of the column can be accurately determined externally by a spherometer technique. The end of the piston is covered with $\frac{1}{8}$ in. of balsa wood to provide decoupling from the mercury column.

The supply of mercury for the variable column is held in a reservoir that completely surrounds the cylinder. The inlet for the mercury is a $\frac{1}{8}$ -in. hole that enters the cylinder at the extreme end nearest the crystal. This makes thin films of mercury backing possible. The inlet must be large enough to provide an easy flow of mercury in and out of the chamber; for if the pressure required to force the mercury out of the cylinder becomes too large, the tolerable stress on the bond between the crystal and support will be exceeded. There is a limit on the maximum size of the inlet, since the mercury in the reservoir must be decoupled from the variable mercury column. A $\frac{1}{8}$ -in. inlet provides adequate decoupling and avoids excessive pressure when the mercury column length is changed.

A further consideration in the design of such a variable resonant frequency crystal transducer for generating sound in liquid media is the coupling of the unit to the medium in which the sound field is desired. The liquid should act as a predominately resistive load for the transducer. If this condition is not fulfilled, the resonant frequency of the system will be shifted because of the reactive component of the liquid loading. This requires that the linear dimensions of the radiating face of the transducer unit be of the order of one wavelength or greater. It also limits the permissible standing wave component in the acoustic field in the "load" liquid in the immediate neighborhood of the transducer. In the present design, this liquid is coupled to the crystal unit

through a thin diaphragm which is rigidly bonded to the unit, as indicated in the figure. A sound absorbing material lines the wall of the sound tank to suppress standing waves.

The source of crystal excitation for producing ultrasound of intermediate intensity for the purpose of studying the characteristics of the unit is an untuned rf driver capable of supplying 300 volts over the frequency range from 10 to 250 kc. The sound field distribution in the liquid medium is determined by a movable crystal probe supported by a coordinate system.

III. EXPERIMENTAL PROCEDURE

The variable resonant frequency crystal system can be analyzed for two operating conditions: (1) the system coupled to air, i.e., very small energy transfer, and (2) the system coupled to a liquid medium, i.e., high acoustical energy transfer. In order to determine operating characteristics of the system under these different conditions, it is convenient to use two separate experimental arrangements for measuring purposes.

We consider first the system when it is coupled to air. Figure 4 shows a schematic diagram of the equivalent electrical circuit of a piezoelectric crystal system vibrating near a resonant frequency. Two branches are shown, the series resistance, inductance and capacitance representing the motional part of the electrical input impedance, and the capacitance C_0 representing the clamped capacity of the crystal.

When the crystal system is vibrating at one of its mechanical resonant frequencies, the motional branch of the equivalent electrical circuit is in series resonance. The input impedance is then a minimum and practically resistive. When the capacitive branch is resonant with the motional branch, the crystal system is vibrating at

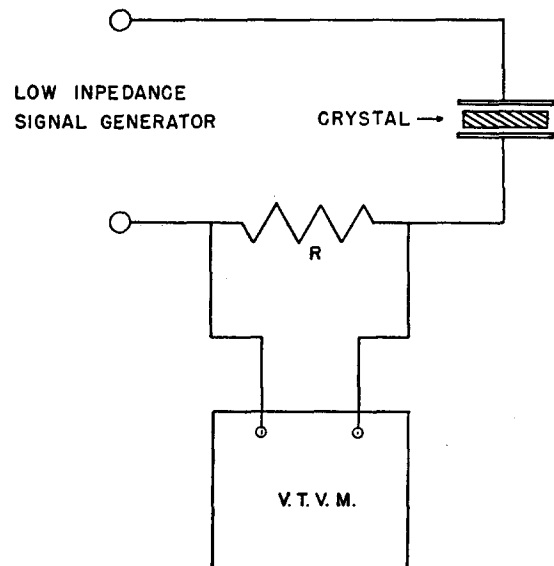


FIG. 5. Experimental arrangement for determining Q' .

antiresonance and the electrical input impedance is a maximum.

A convenient method for determining the magnitude of the electrical input impedance of a vibrating system when losses are small (R small) is illustrated in Fig. 5. The experimental arrangement consists of a resistor in series with the crystal, the combination being placed across the output of a low impedance signal generator. The value of the resistance is kept small compared to the magnitude of the impedance of the crystal. The readings on a vacuum tube voltmeter connected across the resistance are proportional to the current passing through the crystal system. The magnitude of the impedance of the system then follows directly.

A typical experimental curve of the electrical input impedance *versus* frequency for a crystal system radiating into air is shown in Fig. 6. This particular curve applies to a system consisting of a $\frac{3}{4}$ -in. long, $45^\circ Z$ cut *ADP* crystal and a brass backing $\frac{1}{16}$ in. thick. The cross-section dimensions of the crystal are $\frac{1}{2}$ by $\frac{5}{8}$ in. The impedance at resonance and the impedance at antiresonance are approximately 2000 ohms and 2.8 megohms, respectively. These values yield a quality factor for the system of $1.4(10)^3$. The shunt capacity of the leads and holder affect the measurement of the antiresonant impedance and consequently, the value of the quality factor.

When the system is coupled to a liquid medium for high acoustical energy transfer purposes, somewhat different conditions are established. The resistive component of the motional branch in the equivalent electrical circuit of the system is high compared to the impedance of the parallel capacitive branch, and the method outlined above for the determination of the magnitude of the electrical input impedance is not easily adaptable to locating the resonant and antiresonant frequencies. Under these circumstances, we are concerned with the determination of the resonant frequency alone, neglecting completely any consideration of the antiresonant frequency and quality factor. It is convenient in this case to determine the resonant frequency of the system by measuring the relative pressure amplitude of the acoustic disturbance in the liquid medium as a function of the frequency of the electrical generator which drives the transducer. A piezoelectric crystal, operated far from resonance, is used as the pickup probe. The voltage generated by the probe is measured by a vacuum tube voltmeter, the resonant frequency noted as that frequency at which greatest acoustic pressure is developed.

Using the method just indicated for determining the amplitude of the acoustic disturbance in the liquid medium, a comparison was made between the acoustic output for the variable resonant frequency unit and that for a set of fixed frequency crystal units which resonate at various frequencies scattered throughout the band covered by the variable frequency unit. This band extends from 88 to 46 kc, and the fixed resonant fre-

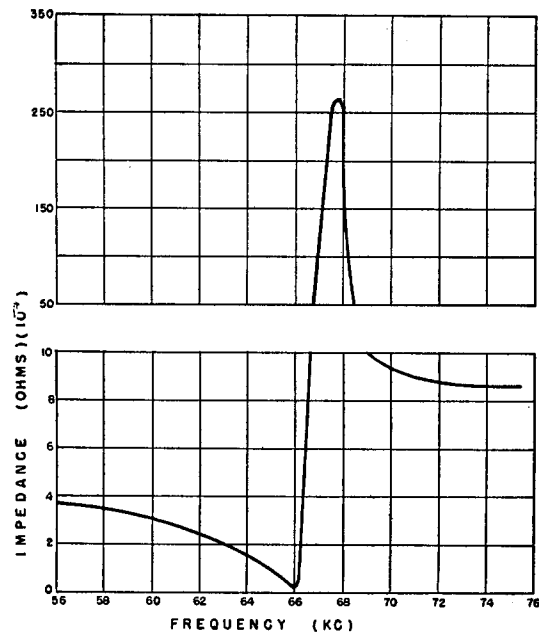


Fig. 6. Electrical input impedance *versus* frequency for a $\frac{3}{4}$ -in. long, $45^\circ Z$ cut *ADP* bar with a brass backing $\frac{1}{16}$ in. thick.

quency units operate at 82, 76, 69, 54, and 46 kc. These units are $45^\circ Z$ cut *ADP* crystals with no backing material and are equal in cross-sectional area to the variable unit. The configuration of the liquid medium with respect to the radiating systems is identical for all units.

The effects of different geometries of the mercury backing, the evaluation of the loss factors, and the operating characteristics of a typical unit are presented in detail in another paper.³

A description of the essential details of construction and testing of a variable resonant frequency unit follows.

The ammonium dihydrogen phosphate crystal is the first consideration in the construction state where orientation and dimensioning are of importance. The edges of the crystal are cut to make angles of 45° with the x and y axes, and the surfaces which will contain the electrodes are cut perpendicular to the z axis of the crystal. Dimensioning of the crystal must be a precise operation to ensure parallel opposite faces. It is not practicable to use inaccurately processed crystals, especially in a multiple unit. Uniform bonding layers and mercury columns are unobtainable when the faces of the crystals are not plane and parallel.

The quality factor and resonant frequency are determined for the free crystal at this stage. The arrangement discussed above, with the crystal in air, is employed for this measurement. The quality factor, Q' , of the free crystal should be at least 1500. Temporary silver electrodes are painted on the crystal for preliminary measurements. After the initial measurements are com-

³ Fry, Fry, and Hall, *J. Acoust. Soc. Am.* **23**, 94 (1951).

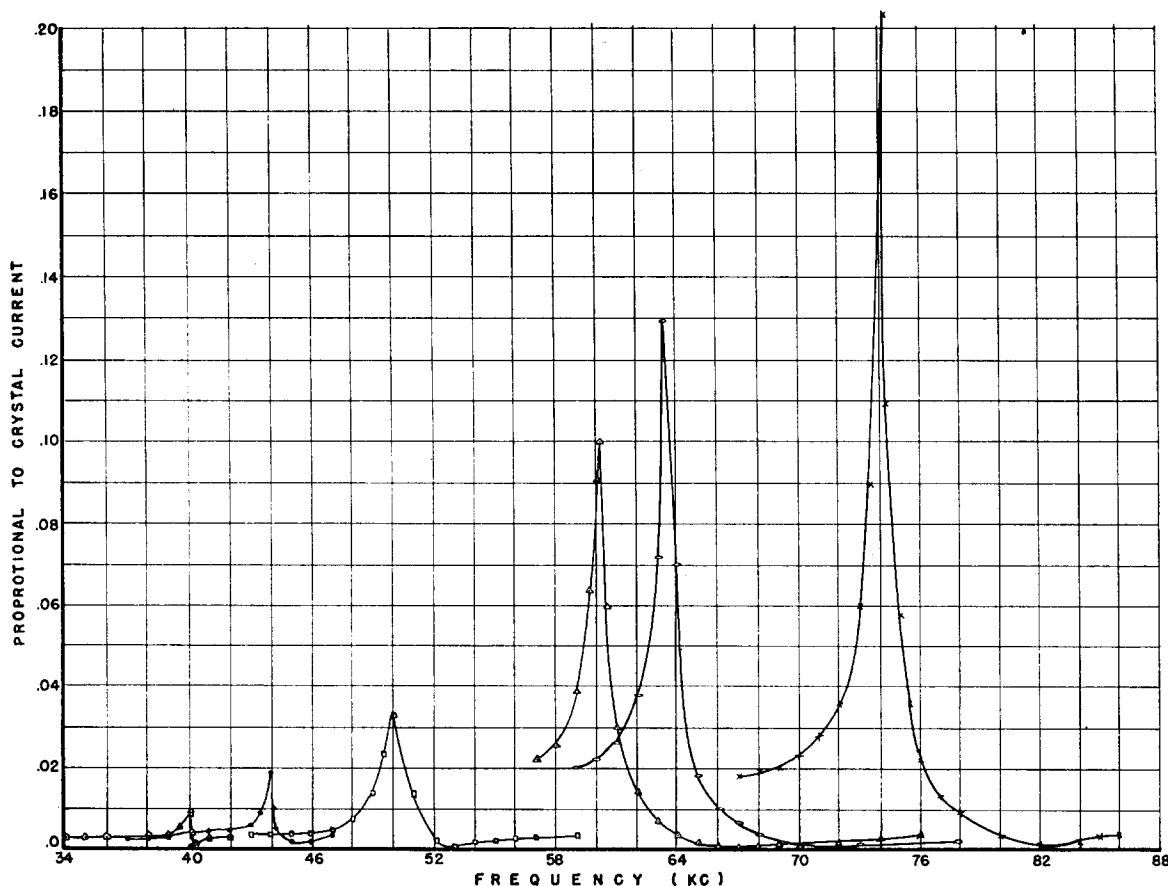


FIG. 7. A series of relative crystal current *versus* frequency curves for a unit operating in air.

pleted, these are replaced by 0.001-in. gold sheets. The gold electrodes are bonded to the crystal in the same manner as the silver-palladium alloy. Thin layers of polyester resin are used to attach the electrodes. This procedure is carried out by a four-hour baking period at 85°C. Tabs are provided for connecting the high voltage leads to the crystal electrodes. Gold is used as an electrode material because of its flexibility.

The radiating surface of the transducer can be increased over that constructed from a single crystal by arranging crystals in parallel. We have constructed units composed of four *ADP* crystals arranged in parallel to give a cross-sectional area of 1.25 sq in. In a parallel arrangement, crystal faces having like polarities are placed adjacent to each other. The resonant frequencies of the individual crystals should be accurately matched when an assembly of this nature is made. The loading conditions of the crystals must be uniform so that the resonant frequencies of the crystals will not be shifted by different amounts in the completed assembly.

A plating of nickel is deposited on the edges and on one face of the silver-palladium alloy prior to bonding the alloy to the crystal. The nickel plate is restricted to the desired areas by masking the surface on which plating is not desired. Glyptol masks have proved satisfactory and this material can be removed easily.

The bath used for the nickel plating, $\text{NiSO}_4(\text{NH}_4)_2\text{SO}_4 \cdot 6\text{H}_2\text{O}$, is the double sulfate of nickel and ammonium. Good results can be obtained when an initial layer of nickel is deposited using a current density of 1.0 amp/in.². After 5 sec, the current density is reduced to 0.15 amp/in.². Nickel layers 0.0005 in. in thickness are normally used.

The crystal is supported over the opening of the mercury housing by a balsa wood plate. The crystal unit is rigidly coupled to the balsa wood by the polyester resin near the end of the unit on which the Ag-Pd alloy will be bonded. The dimensions of the hole in the balsa wood are such that a minimum of pressure is applied to the crystal. The joint is mercury tight by virtue of the bonding material and not because of a tight fit of the crystal into the balsa wood.

The balsa wood and Ag-Pd alloy are bonded to the *ADP* crystal unit in two separate baking operations. First, the balsa wood is bonded to the unit. The crystal must be perpendicular to the plane of the wood since accurate alignment of the crystal with respect to the mercury column is desirable. In the second operation, the Ag-Pd alloy is bonded to the composite crystal-balsa wood system. Both baking operations should be done at relatively low temperature. Our results indicate that the polyester resin is polymerized in 4 days at a

temperature of 40°C when a catalyzer is used. The bonding of the balsa wood to the unit can be done at somewhat higher temperature to speed the construction process. A temperature of 85°C will result in polymerization in 4 hours when one percent (by weight) of the catalyst is added.

The condition of the bonds at the interfaces between parts of the system is extremely important from the point of view of internal losses. Such losses will be high if the bond between the crystal and a backing material is poor. A poor bond may result because of gaseous inclusions, slipping, or the use of high loss materials.

At this point in the construction of the variable resonant frequency unit, the composite crystal-metal assembly is rigidly coupled to a system which provides connections for high voltage leads and supports the unit over the mercury column. The quality factor should be of the order of 600 at this stage in the assembly.

The surface of the Ag-Pd alloy is amalgamated before coupling the mercury column to the unit. The alloy is subjected to a dilute solution of hydrochloric acid just before applying mercury to the surface. Mercury is placed on the clean surface of the alloy which has been wiped free of acid. Rubbing is often necessary to distribute the amalgamation uniformly over the surface.

The amalgamation process has a tendency to improve over a period of roughly one month, as manifested by a monotonic rise in the quality factor of the variable resonant frequency crystal unit over this period. Units that have been in operation for ten months exhibited an increase in quality factor for the first month and relatively constant Q' for the remaining months.

The crystal is mounted on the metal support by clamping the balsa wood over a gasket. A soft raw rubber is used to yield a mercury-tight system. The depth of the gasket groove is designed to give a minimum of deflection to the rubber. The lightest possible pressures are employed so that a minimum of permanent set is assumed by the balsa wood. Permanent deformation of the wood makes mercury-tight seals practically impossible.

The alignment of the crystal unit with respect to the mercury column is critical. The available adjustment of various components relative to one another is very slight with this system. Accurate machining and precise bonding are relied upon to give the proper alignment. If the end of the mercury column is not parallel to the end of the crystal unit, multiple resonant frequencies occur. For longer lengths of backing, when the amount of non-uniformity is small compared to the length of the column, the misalignment causes Q' to decrease for intermediate shifts and increase again for larger percentage shifts of the resonant frequency.

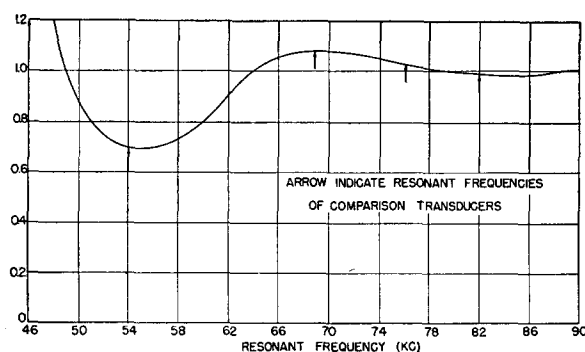


FIG. 8. A graphical comparison of the acoustic outputs of fixed and variable resonant frequency systems.

At this point in the construction of the system, measurements of the reduction of the resonant frequency as a function of the length of mercury backing can be made. The quality factor, Q' , and the resonant frequency for various lengths of backing can be determined by the method described above for low loss systems.

The graph of Fig. 7 consists of a series of relative crystal current *vs* frequency curves for the nonradiating system (air). The data were taken at various frequencies, all of which are in the band covered continuously by a single variable frequency unit. These curves illustrate the variation in the impedance of a variable resonant frequency unit as a function of the resonant frequency. The first curve corresponds to a resonant frequency of 74 kc for the unit. The quality factor is 450 and the Q , as measured at the half-power points, is approximately 250. The quality factor at the lowest resonant frequency indicated (40 kc) is 10, and the Q is 100.

The variable resonant frequency crystal system is coupled to the liquid medium through a 0.003-in. cellophane diaphragm. The area of the cellophane is slightly larger than the area of the unit. Figure 8 shows a graph of the ratio of the power output of the variable frequency unit to that of a set of fixed frequency units under equal driving electric field strengths.

IV. CONCLUSION

A stable low loss variable resonant frequency crystal system has been developed which operates over a 2:1 frequency range. It can be used as a generator of ultrasound over this range (40 to 80 kc) with an output power at any selected frequency comparable to that of a fixed resonant frequency unit of equal radiating area operating at resonance under an equal driving electric field strength.

ACKNOWLEDGMENT

We wish to thank Mr. Frank J. Fry for contributions to this investigation.