QUARTZ CRYSTAL UNITS FOR HIGH G ENVIRONMENTS

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Summary Quartz crystal units are commonly used to achieve frequency accuracy of the order of 100 parts per million or better. The usual crystal mechanical environments are quite benign compared with those encountered In high g telemetry, however, and the normal shock tests are only 100 g’s. The preliminary, design of a ruggedized high frequency crystal unit is shown as well as test date on the behavior of these units when subjected to 15,000 g’s of impact shock. A crystal resonator is quite fragile since at 20 MHz an AT resonator is only 3 thousandths of an inch in thickness. Higher frequency units appear to have a g limit only slightly in excess of 20,000 g’s. At lower frequencies, the resonator is not the limiting element but the supports and bonds become unreliable. A trade-off must be made between a very stiff support, which will increase the acceptable g level, and the concomitant frequency instability due to changes in mechanical stress on the quartz resonator. These stress changes can be caused both by differential thermal expansion of the mount and quartz as well as by shock Induced effects.

Introduction Quartz crystal units, are used in many applications where a frequency stability of 1×10^{-4} or better is required. Since the quartz resonator must be free to vibrate without any appreciable mechanical damping, the mounting is placed at points of minimum notion. This leads, in the commonplace crystal, to a rather fragile mounting. Many crystals are mounted on thin piano wire spring type suspensions to reduce mechanical strains in the resonator that cause frequency-temperature perturbations. The problem resolves itself to one of achieving the optimum design with respect to a substantial mounting and yet not have a mount that is so stiff that large frequency changes occur because of differential expansions between the mount and the resonator or appreciable changes in strain due to shock effects upon the mount. Relatively little work him been accomplished in this area except for that reported by the Harry Diamond Laboratorles.[1] Several groups of crystals were fabricated in the Electronic Components Laboratory, using a new method of bonding, and subjected to a steady state 20,000 g’s acceleration and a 15,000 g gun type shock. For g levels exceeding 20,000, the

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[1] P. T. Liss, J. F. Richardson, “Ruggedized Quartz Oscillator Crystals for Gun Launched Vehicles,” TM-68-23, Harry Diamond Laboratories, Washington, D. C. 20438.

evaluation of a stiffer mount and a thicker resonator will. be undertaken since preliminary data indicates the:initial design was inadequate In these two respects.

Crystal Unit Design A crystal unit consists of a quartz resonator, electrodes, mounting, conductive bond, and a hermetically sealed enclosure. The high frequency crystal unit makes use of the AT-cut since it has the lowest frequency-temperature coefficient of any orientation. This type of resonator is mechanically active In the center and can only be mounted alone the outer edges. There is a restriction on the minimum diameter of the resonator since some acoustic energy propagates through the resonator and with very small diameter units, the edge losses become quite high. The first design tested was a small resonator bonded to 10 support leads in a TO-5 type Holder.

Figure 1 is a photograph of several units, one of which is a conventional crystal resonator mounted on piano wire support. This crystal would be almost useless for any application where the shock levels exceed 50 g's. Two of the units are of the never type tested and show the use of stainless steel ribbon support, nickel electroplated bonds, and a resonator 0.2 inch in diameter. It has been determined that the use of a metallic bond results in increased mechanical strength as compared with the usual cemented type. None of the crystals tested failed because of inadequate bond strength. Every AT crystal manufactured now usea conductive epoxy or bakelite cement. When this material. Is properly handled, the bonds are adequate for most applications but frequently the use of this material results in crystals with very little bond strength. The fourth item in the picture shows the result of crystal resonator failure during the shock test. The first test conducted at Aberdeen Proving Grounds was not conclusive with regard to the failure mechanism of this design when subjected to 15,000 g's of shock. The method of packing the crystals in the projectile subjected the enclosures to a very large compressional force. This deformed the cans to a degree that the mount was subjected to a direct and large pressure. Many crystal resonators broke because of the twisting force placed on the supports. It is of interest that in every instance, the quartz under the mount clip was still firmly held by the electroplated Ni bond.

Figure 2 is a sketch of the method used to bond the quartz resonator to the stainless steel ribbon supports. The conventional method, using conductive cements, depends upon the proper condition of the cement as well as the correct amount of silver flake for adequate adherence and conductivity. Too little flake results in good bonds that are lossy or even nonconductive. Excess flake results in good conductivity but poor adherence. The new method depends upon a thin layer of low stress nickel (Ni) plated onto a chromium-copper (Cr-Cu) film which is strongly adherent to quartz. The Cr cannot be electroplated because of a layer of oxide which forms on Its surface. Near the end of the Cr evaporation cycle, Cu is evaporated simultaneously with the Cr. Finally, only copper is evaporated to form a pure copper top layer. Because of mixing of the two metals during the evaporation cycle, the Cu is strongly attached to the Cr. The final operation, after inserting the resonator into the clips, is the electroplating of low internal stress Ni from a nickel sulfamate Plating solution:[2] onto both the crystal tabs and the stainless steel clips. This is done by first flashing the Ni with a current of 10 milliamperes/ crystal unit for a few seconds and then reducing the current to 1.5 ma/ crystal unit for 90 minutes. This results in the deposition of approximately 0.5 thousandths of an inch of Ni and tests have shown pull strengths of 6 pounds or more for this film thickness. The next operation involves the evaporation of Au electrodes upon -the center area of the crystal resonator while monitoring the oscillation frequency. Material is evaporated until the desired frequency is reached. The rest of the processing is entirely conventional.

Crystal Test Results As mentioned, the first group of ruggedized crystal units assembled in the Electronic Components Laboratory used the TO-5 Holder with ten support leads. A small stop was formed in the upper end of each of the ten leads and the 0.2 inch diameter ban's was placed on these steps and bonded with conductive epoxy cement. This resulted in a very rugged and stiff mount. The relatively large frequency changes which occurred with these units is due to the severe strain imposed on the crystal resonator by the mounting and bonding method. This approach was abandoned in favor of a less expensive and more practical means which make use of a 2 point mount in Holder W-25/U.

The second group of crystal units were assembled in Holder NC-25, and then subjected to radial acceleration in a centrifuge at approximately 20,000 g's. One unit out of 15 failed; the cause of failure was found to be due to fracture of the quartz resonator. The fundamental frequency of these units was 17.5 MHz. The use of the centrifuge to screen out potentially defective crystals is considered very worthwhile. A microscopic examination of the quartz resonator after final lapping is also useful since it has been noted that small cracks and fractures do occur during lapping. Failure of the resonator with this kind of defect is certain; a shock will cause the fracture to expand quickly until the resonator completely fractures. It was found that the permanent frequency change due to the 5-minute 20,000 g centrifuge test was 0.8 parts per million (ppm) with a one sigma deviation of 0-5 ppm.

The units that had been centrifuged, plus an additional number, were taken to Aberdeen Proving Grounds and tested in the Ballistics Research Laboratory high-g lead test facility. The first group of eleven units were fired at 15,000 g and 7 units failed. The second group were fired at a nominal 20,000 g and all 12 units failed. The copper ball accelerometer indicated a g level of 40,000 for the second firing. It is believed that a major cause of failure during this initial test was the deformation of the HC-25 enclosure by the powdered material used to pack the crystals in the projectile.

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[2] Type SN, Sulfamate Nickel Plating Solution, Allied Research Products, Inc., Baltimore, Maryland 21205.

The first test firing was conducted such that acceleration forces were applied to all three axis of the crystal, unit. Figure 3 is a sketch which shows the optimum acceleration direction, based upon the relative stiffness of the quartz resonator and mounting system. In the first test firing, only crystals mounted in the position marked “best” survived. Even in the 15,000 g test, all crystals mounted In the directions labeled “poor” failed, although it in probable that some of the units failed because of the damage sustained by the crystal holder.

A third group of 10 crystal units were fabricated at 16-5 MHz and the metal holders were inserted in a series of milled cavities In an aluminum cylinder. The glass bases of the holders were exposed to the powdered rock packing In the projectile. After the 15,000 g, 2-5-millisecond shock, It was found that every glass base had cracked. The measured frequency change of the 16-5 MHz crystals was -8.4 ppm, with a one standard deviation (1σ) of 2.9 ppm. The crystal resonators were sealed in a dry atmosphere to reduce aging effects; previous experience has shown that a large negative frequency change can be expected when the hermetic seal is broken. Quartz can and does attract and hold water vapor and it is this effect that causes negative frequency aging in unsealed holders.

A fourth group of crystals, processed at 19 Mz, were imbedded in the aluminum cylinder with a second piece of aluminum placed such that the glass base of the holder would be protected from the rock dust material.

Figure 4 is a table that shows the frequency changes which resulted when the various groups of crystal units were subjected to steady state and shock accelerations.

To Improve the performance; that is, to increase the likelihood of survival at higher g forces, it now appears that a thicker resonator must be used. It is also necessary that more attention be paid to the various lapping stages during the processing of the quartz resonator to avoid incipient cracks and fractures. While the Ni bond has shown excellent strength, the quartz resonator has shown a tendency to fracture easily. The stainless steel supports can be increased in thickness to improve the ruggedization in the plane through the mounting points. A limit is reached, however, because of the deleterious effect upon the frequency temperature coefficient of the crystal unit when the mount has insufficient flexibility.

A quartz resonator is sensitive to linear acceleration. An investigation by the Bell Telephone Laboratories[3] shoved frequency changes of $+16 \times 10^{-9}$ for a 30 g acceleration. While the work was intended to determine means for minimizing the effect, changes as large as 1×10^{-7}(/30 g were noted. The orientation angle of the quartz resonator can be

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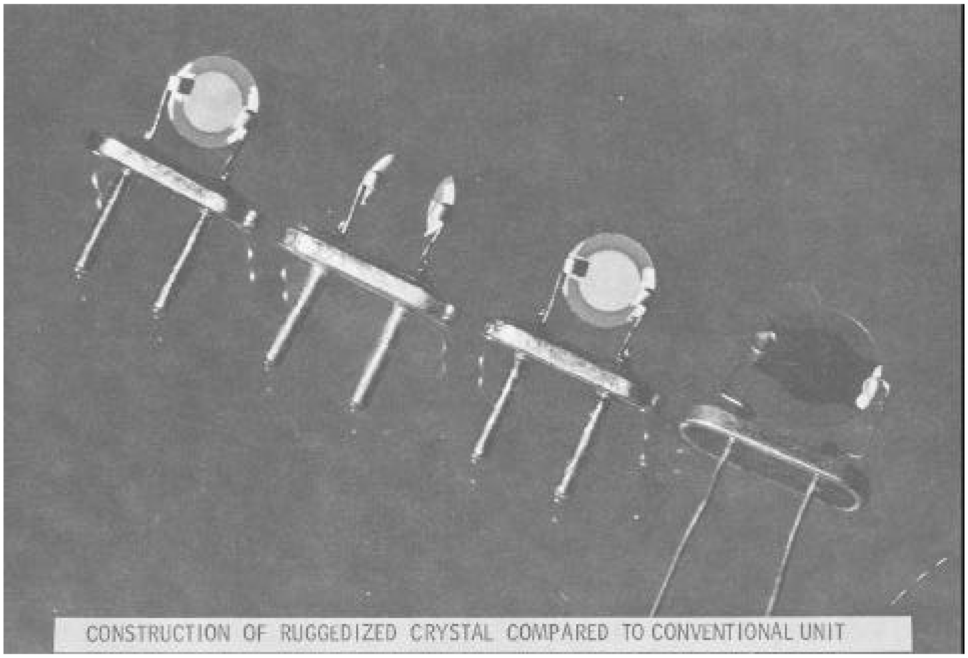
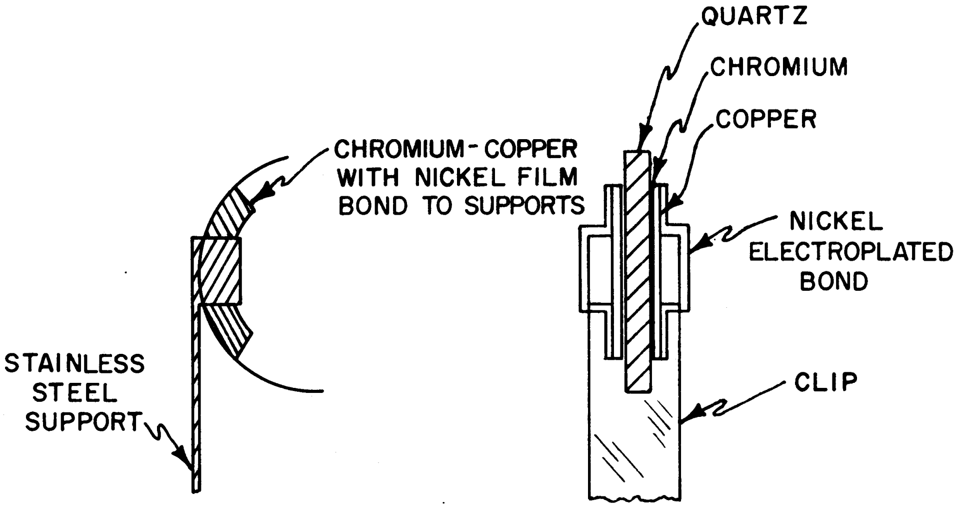
[3] W. L. Smith & W. J. Spencer, “Quartz Crystal Controlled Oscillators,” Report No. 253359, Contract DA36-039 SC-85373, pp. 12-14, 15 March 1963.

optimized for temperatures of ±30°C of room temperature and a frequency stability of ±3 x 10^{-6} achieved over this 60°C range. The temperature change of the crystal unit will be very small during a typical gun launch so it appears feasible to measure the acceleration of the projectile while it is in the gun barrel by simply measuring the transmitted frequency. It would be necessary to perform a g-frequency calibration in a centrifuge prior to the test firing since each crystal unit will have a somewhat different sensitivity to acceleration.

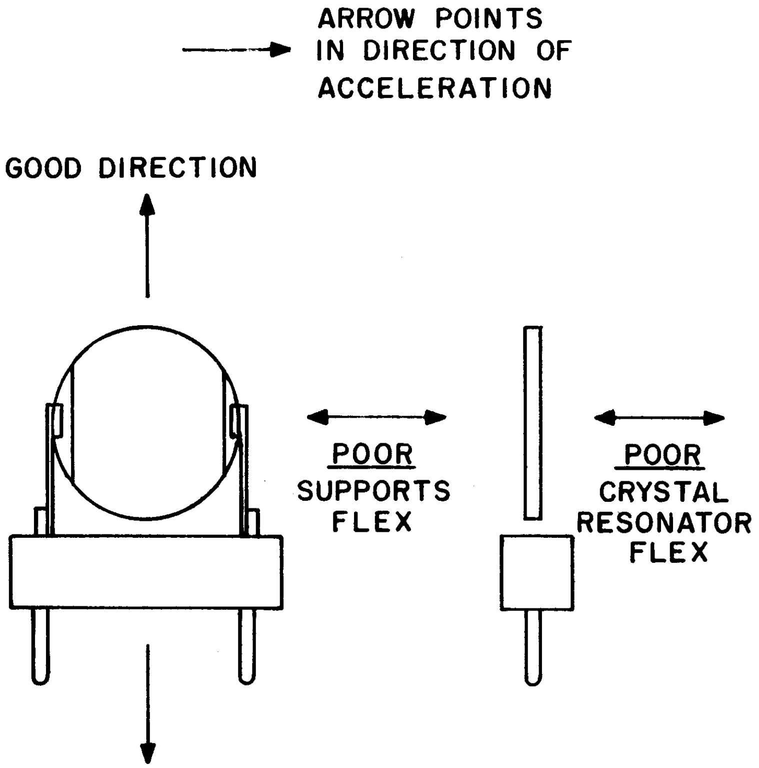
Conclusion A relatively small scale investigation of the design of crystals suitable for high g use indicates substantial possibilities for improved units. Initial design units, gun-launched in the most favorable direction of acceleration, shoved good survivability and small frequency changes. Additional design work and testing should result in crystals capable of surviving 40,000 g or more. A trade-off between frequency change, as a result of the high g shock, and ruggedization is necessary. In applications where the required frequency stability is of the order of 1 x 10^{-5} or better, it does not seem practical to develop a unit capable of withstanding forces exceeding 20,000 g1s. Where substantial frequency changes can be tolerated, 5 to 10 x 10^{-5} , then a very stiff mount can be used and this will result in a significant increase in the tolerable g rating.



CONSTRUCTION OF RUGGEDIZED CRYSTAL COMPARED TO CONVENTIONAL UNIT



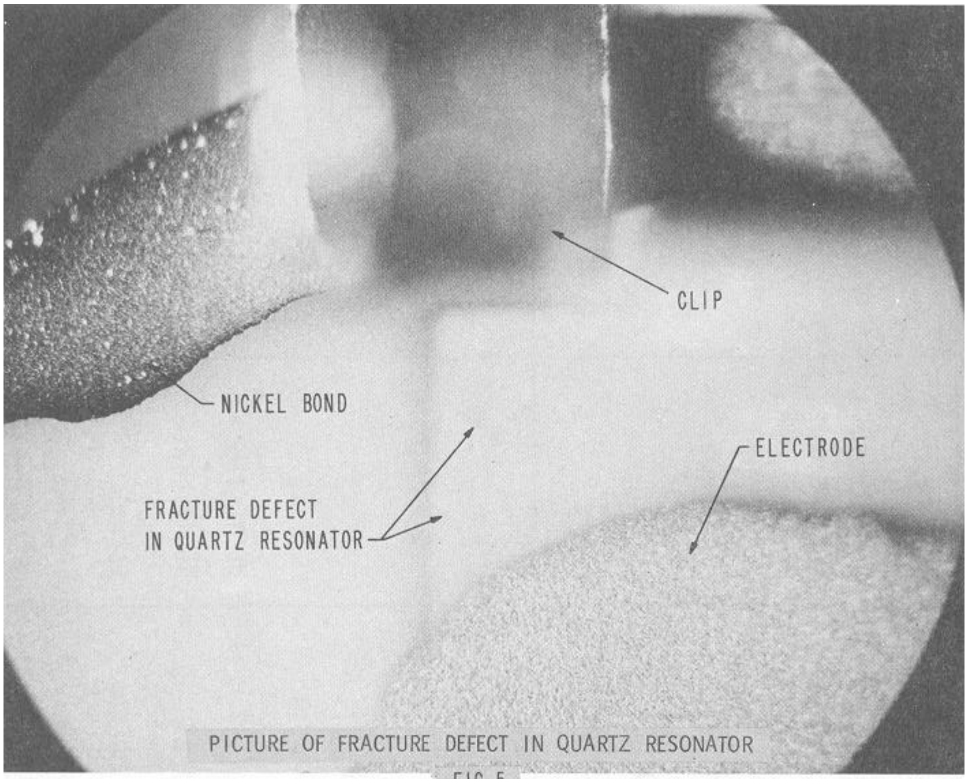
DRAWING SHOWING CRYSTAL CONSTRUCTION



DRAWING SHOWING RELATIVE PERFORMANCE OF CRYSTAL IN 3 ACCELERATION DIRECTIONS

	TEST NUMBER & HOLDER TYPE				
	1 TO-5	2 HC-25	3 HC-25	4	5
TEST CONDITIONS	A. 15,000 G SHOCK B. 20,000 G CENTRIFUGE	A. 15,000 G SHOCK B. 20,000 G CENTRIFUGE	A. 15,000 G SHOCK	A. 15,000 G SHOCK	
TEST RESULTS FREQUENCY CHANGE IN PARTS PER MILLION (PPM)	A. 48 ppm AV 76 ppm 1σ B. 11 ppm AV 10 ppm 1σ NO FAILURES	A. 4 ppm AV 3.7 ppm 1σ B. 0.8 ppm AV 0.5 ppm 1σ 19 OUT OF 23 FAILURES HOLDERS DAMAGED IN TEST	A. 8.4 ppm AV 2.9 ppm 1σ 10 TESTED NO FAILURES BASES DAMAGED IN TEST	A. 4.6 ppm AV 3.5 ppm 1σ 8 TESTED 1 FAILURE	

TABLE SHOWING PERFORMANCE OF CRYSTALS UNDER HIGH G TESTS



PICTURE OF FRACTURE DEFECT IN QUARTZ RESONATOR

FIG. 5