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Crystal Resonators with Increased Immunity to Acceleration Fields

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Abstract—Resonator configurations are described that are compensated for arbitrary directions of the acceleration field and that require no additional electronics other than the oscillator circuitry normally used. This approach produces compensation with no changes in size, weight, and power, and applies to any crystal reference oscillator in any shock/vibration environment.

INTRODUCTION

FREQUENCY PERTURBATIONS are produced in thickness mode crystal resonators by acceleration-induced body forces. These forces are distributed throughout the resonator volume and vary with the acceleration direction. For specific acceleration directions, the effect can be sharply reduced by changing the points of application of the mounting supports. Even doubly rotated cuts may be accommodated (although the mounting design varies with cut), and for some of these cuts the effect is further reduced below the value found for the *AT* cut. When the acceleration direction is known in advance, positioning the resonator with respect to this direction minimizes the problem.

In high shock and vibration environments such as in helicopters, tanks, and other vehicles, and the more moderate environments of manpack and aircraft collision avoidance system use, accelerations occur in arbitrary directions with ensuing large frequency shifts in the crystal resonance frequency. When the acceleration is arbitrarily oriented with respect to the resonator, no crystal cut and/or combination of mounting supports can by themselves produce cancellations

of the frequency perturbations to the extent required, e.g., by secure communications systems. However, by taking advantage of the experimental fact that the resonance frequency shift changes sign with reversal of the acceleration direction and the fortunate happenstance that quartz occurs in right- and left-handed pairs, composite resonators of either discrete or stacked varieties may be fashioned having vastly decreased acceleration sensitivity, whatever the acceleration direction may be, with no concomitant degradation of any of the desirable resonator properties. The approach is applicable to doubly as well as singly rotated crystals, so that the additional nonlinear compensation of thermal transients, etc., that occurs for these cuts can be had along with acceleration hardening.

ACCELERATION EFFECTS

In the static force-frequency effect [2]–[16], forces and moments acting on the peripheral boundary of a crystal resonator serve to produce frequency changes in the resonator. Accelerations of the crystal plate, on the other hand, produce distributed body forces throughout the resonator volume that are communicated at the crystal boundary to the mounting supports. The stress distribution within the crystal depends not only upon the mounting points, but also on the direction of the acceleration. In general, the static and dynamic effects will produce different states within the vibrator, and different frequency shifts [17]–[33]. Some applications of the effect to realize accelerometers have been made [24], but much more often the effect is highly undesirable, and efforts to reduce the effect have continued for the past twenty years [17], [32].

Within the past five years the problem has become particularly acute, due to exacting requirements arising from the

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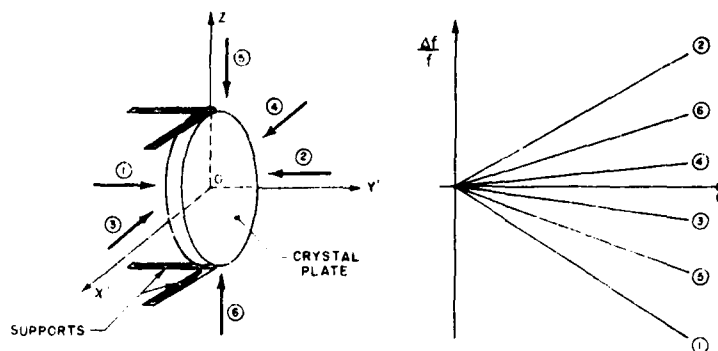


Fig. 1. Resonator frequency change versus magnitude and direction of acceleration field. Frequency shift reverses sign with reversal of acceleration direction. Experimental results for AT cut quartz in two-point mount (after Valdois [20], [21]).

present and projected secure digital systems for communication, command, and control, and for navigation/position location. Fortunately, during this interval a number of advances have come about that in combination promise a significant reduction in the acceleration sensitivity of crystal resonators. One of these developments is the introduction of doubly rotated cuts [10], [11], [34]. Another is the use of new support configurations [33], [35], [36]. Additional developments will be detailed in ensuing sections.

Concurrent with these developments, a nonlinear theory has been fashioned by Lee and his coworkers that describes the force-frequency effect [7]–[9] and acceleration effects in singly rotated, rotated Y-cut quartz plates [27], [29]. A plate theory has also been developed for doubly rotated quartz cuts [37]. Such a theory will provide a necessary understanding of the mounting support problem as applied to acceleration-compensated resonators.

ACCELERATION COMPENSATION

One of the most recent acceleration compensation schemes is the systems approach of Przyjowski [26], [28], [31]. In it, ancillary accelerometers sense the applied acceleration components along three orthogonal directions, and this information is used to feed back a compensation signal to correct the crystal frequency. This arrangement provides improvements of a factor twenty or so over an uncompensated resonator and works for arbitrary directions of applied acceleration.

Another acceleration compensation scheme is that of Gagnepain and Walls [22], [33], [35]. In this arrangement, two quartz vibrators are connected electrically in series, in the manner used long ago by Koga [38], [39] to effect temperature compensation. Now, however, the crystals are oriented so that the axes along which the acceleration-frequency effect is greatest are antiparallel in pairs. According to the measurements of Valdois [20], [21] for AT-cut disks supported along the Z' axis, the directions of greatest acceleration sensitivity are for acceleration fields along the Y' axis, which coincides with the disk thickness, and for fields along the Z' axis. Because the sensitivity is least for X-directed fields, the disks are oriented so that the X axes of both disks are parallel, and the Y' and Z' axes are antiparallel. Then compensation is achieved for directions of acceleration lying in the plane normal to the

common X axis. The experimental arrangement and results of Valdois are shown schematically in Fig. 1.

A configuration alternative to that of Gagnepain and Walls was proposed by Vig [40], wherein the two paired resonators are mated in the fashion of a two-layer stacked crystal filter [41]–[43]. In this case the angle ψ between the X axes of both crystals would be zero. The acceleration-frequency behavior would be similar to that of the discrete configuration, but the stack would be more robust and occupy less room than two separate vibrators.

ENANTIOMORPHOUS CRYSTALS

Two identical crystal resonators can only be manipulated so that an even number of their respective crystal axes are antiparallel. Reversal of an odd number requires an improper rotation. Fortunately, just such an operation is possible with quartz! The operation changes the handedness of the crystal. The existence of right- and left-handedness in a crystal is known as enantiomorphism. When two crystal resonators, identical except for their handedness, are used as a pair, they may be oriented with all three corresponding axes antiparallel. Then, from the results shown in Fig. 1, where the frequency change reverses sign with reversal of acceleration direction, paired resonators will suffer no frequency shift for any direction of the acceleration field. This statement holds for pairs configured as discrete vibrators, or as a composite stack.

Quartz is not the only enantiomorphous crystal. Any representative of the eleven crystal classes 1, 2, 222, 4, 422, 3, 32, 6, 622, 23, and 432 exhibits this property. These are the classes without a plane of symmetry. The enantiomorphs bear a mirror image relationship to each other; all are non-centrosymmetric, and hence (with the exception of class 432) are piezoelectric. There is at least one representative from each of the seven crystal systems. Berlinit, α - AlPO_4 (class 32) is enantiomorphous, lithium tantalate and lithium niobate (class 3m) are not.

In the following, it will be convenient to use coordinate systems having the same chirality as the type of quartz: left for left-quartz, right for right-quartz. This convention was first proposed by Koga [44] in 1929 and adopted in a 1945 report by the IRE, following a paper by Cady and Van Dyke [45]. It is also used in Cady's book [46]. The 1949 IRE

standard adopted a right-hand coordinate system for both forms [47], and the latest IEEE standard has continued the convention of its predecessor [48]. A recent paper by Donnay and Le Page [49] lucidly sets forth reasons for using two coordinate systems for enantiomorphs. Incidentally, morphological enantiomorphism appears first to have been explicitly recognized by Louis Pasteur; the usual attribution is to Haüy who illustrated both types of quartz, but his writings do not show that he recognized the difference [50]. The question of priority is still very much an open one [51], [52].

The enantiomorphs discussed here correspond to what is called Brazil, or optical, twinning in natural quartz. The other category of twinning often present in natural quartz is Dauphiné, or electrical, twinning, where the two forms are rotated with respect to each other about the Z (or optic) axis so that the X axes are in opposite (antiparallel) directions, but the handedness is unaffected. Dauphiné twinning may be brought about relatively easily and involves small changes in atomic positions, whereas Brazil twinning requires the breaking of atomic bonds and a significant expenditure of energy [53], [54]. Yoda proposed the use of electrically and optically twinned quartz for crystal vibrators before cultured bars attained the degree of use that they enjoy today [55].

If a left- and a right-handed AT cut are oriented so that their axes are, respectively, antiparallel and connected electrically in series or in parallel, then the combination becomes insensitive to acceleration fields of arbitrary orientation, provided that the symmetry of the mountings is maintained [33], [35]. This is the discrete configuration, where the crystal plates are physically unjoined.

STACKED CRYSTAL STRUCTURES

The stacked crystal configuration came about originally for filters [41]–[43] when used in the multimode configuration. Layered structures utilizing a single mode have been more commonly used [56]–[63]. Here we discuss the stacking of two enantiomorphous pairs with respective axes antiparallel, and operated as a single resonator of composite form. Both crystals are of identical design; that is, they have identical individual frequencies, electrode patterns, and so forth. Fig. 2 gives the four possible two-crystal structures. The two on the left in the figure are connected electrically in series; the two on the right are in parallel electrically. The upper two are arranged so that the electric fields in the two crystal plates are antiparallel; the bottom two structures have electric fields that are parallel in the two crystals. For the upper structures, the odd harmonics (of the composite taken as a whole) are driven, while the even harmonics are driven in the two lower structures. In the upper left and lower right configurations, an insulating film or layer between the crystals is necessary for operation, and large values of capacitance would be associated therewith, to the detriment of the composite's performance. This leaves the two configurations of Fig. 3 as the simplest and most practical stacked crystal resonators for acceleration immunity. The structure on the left of the figure consists of two crystal plates connected electrically in parallel, using a common central electrode. It operates at odd harmonics of the fundamental frequency of the composite, i.e., at one half,

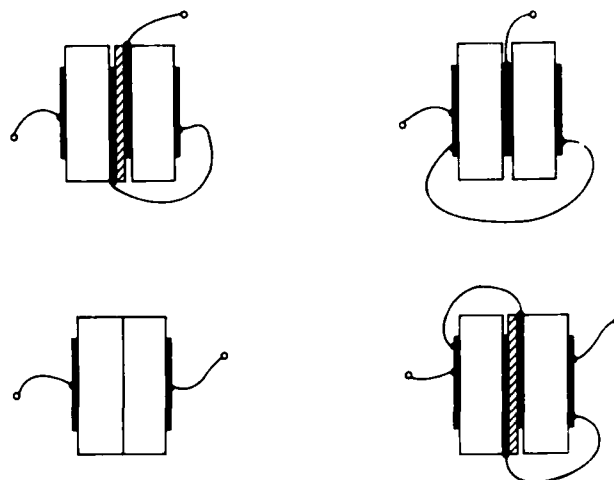


Fig. 2. Stacked crystal vibrator configurations. In the upper structures the odd harmonics of the combination are driven; the even harmonics are driven in the lower structures. Solid areas denote electrode metalizations, and cross-hatched areas are insulating films.

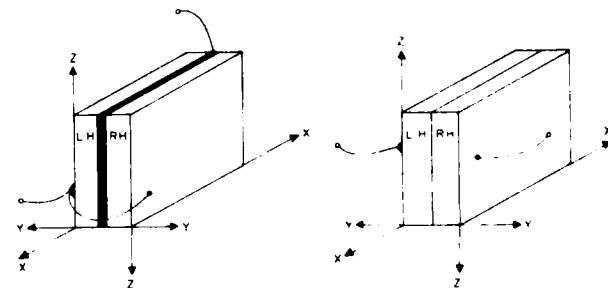


Fig. 3. Simplest stacked crystal vibrators as paired enantiomorphs. In practice, preferred lateral contours might be circular, or of special polygonal outline [16].

three halves, etc., of the frequency of each crystal plate operated separately.

The structure on the right side of Fig. 3 is the series version of the stack, and operates at even harmonics. A central electrode is not even necessary in this configuration. Provided the plates to be joined have flat mating surfaces and are sufficiently clean of contaminants, they will adhere due to van der Waals forces. An apparatus that can be used for this purpose is nearing completion [64].

Implicit in the foregoing discussion have been assumptions that the stacked crystal composite vibrator consists of two crystal twins that each operate in a single mode, and that, when the two vibrators are joined, the composite continues to operate in this manner. For the singly rotated cuts (YXl) Θ of quartz, including the AT and BT cuts, it is easy to see that this will be the case, since each vibrator is driven in a pure shear mode by a thickness-directed electric field. This mode has particle motion strictly in the plane of the plate so that, when the two plates are joined, the composite will also have motions in the plane of the plate; the phase of the motions in the two component plates will depend on how the electrodes are connected, and hence, on whether the electric fields in the

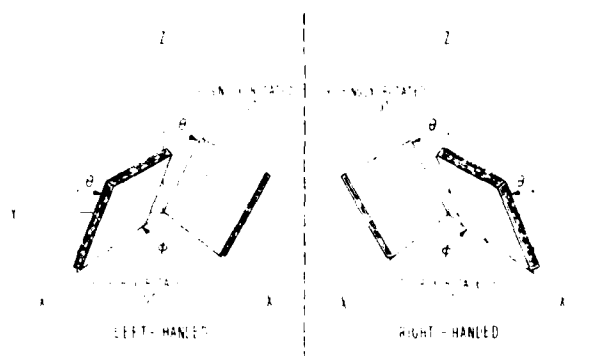


Fig. 4. Singly and doubly rotated cuts defined for left- and right-hand crystal pairs. Corresponding cuts are mirror images.

two plates are parallel or antiparallel. The phase will dictate whether even or odd harmonics of the composite are driven.

The most important recent development in the area of high precision frequency control has been the introduction of doubly rotated cuts of quartz, (in particular the SC cut), having compensation of certain nonlinear elastic effects that otherwise cause very undesirable stress-frequency [65], [66] and thermal transient/thermal gradient-frequency effects [67]–[70]. It is an experimentally observed fact that SC cuts are also considerably less sensitive to the effects of acceleration (attitude, shock, and vibration) than AT cuts; the improvement may be as much as a factor of ten. For these crystal cuts the three piezoelectrically driven modes all have particle motion that is neither parallel to, nor perpendicular to, the plate normal. It is not clear, therefore, that such plates can be used in the stacked configuration for acceleration compensation in the manner described above. This will now be demonstrated.

DOUBLY ROTATED ENANTIOMORPHS

Both singly and doubly rotated enantiomorphs are shown in Fig. 4. It is seen that the mirror-image property holds for any orientation. Assume that a doubly rotated cut, e.g., the SC cut, has been fashioned in both right- and left-handed forms; also assume that the corresponding plate axes have been simply labeled X , Y , and Z (instead of double-prime axes). Now suppose that a portion of each plate is considered to have dimensions such that the eigenvector corresponding to the mode in question points in the direction from an origin zero along a major diagonal of the rectangular prism as seen in Fig. 5. On the left is the left-handed plate (or portion thereof), with particle motion along OA ; the motion thus has components both along and perpendicular to the major plate surfaces. The mirror image right-handed plate seen in the center of Fig. 5 has particle motion along OB , because OB is the mirror image of OA . In order to orient the right-handed plate so that its axes are antiparallel to those of the left-handed plate, and thereby achieve the configuration for acceleration compensation, it is only necessary to rotate the center drawing in Fig. 5 about the Y axis until the rightmost drawing is reached. Then the line OB , seen in the right portion of the figure is exactly in line with OA seen in the left portion of the figure. The stacking thus can take place without any

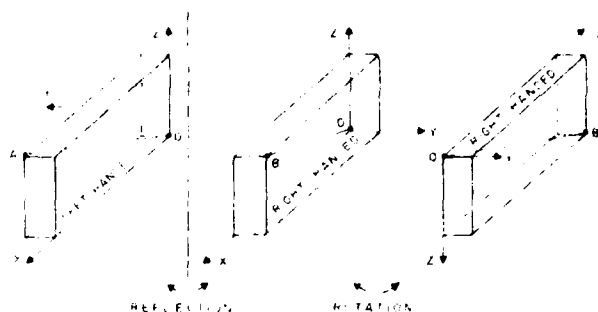


Fig. 5. Demonstration of compatibility of stacked, doubly rotated, enantiomorphous pairs. Solids are elemental volumes of plate resonators chosen so that vibratory motion of the mode in question lies along body diagonals. Reorientation of left- and right-handed pairs as required for acceleration compensation results in parallel, and therefore compatible, displacements.

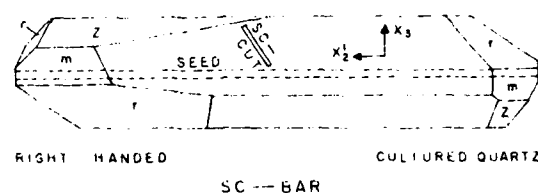


Fig. 6. Line drawing of right-handed cultured quartz SC-bar, seen looking down the $+X_1$ axis. Position of SC cut is indicated, along with natural crystal faces.

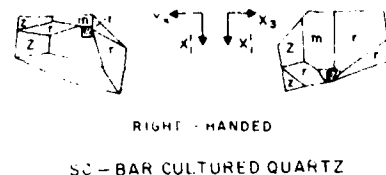


Fig. 7. Line drawing of right-handed cultured quartz SC-bar, seen looking down the $+X_2$ and $-X_2$ axes. Cross-hatched regions represent location of seed. Natural crystal faces are indicated.

difficulty; the argument holds for all three plate thickness modes, with the conclusion that doubly rotated plates may be stacked as readily as singly rotated plates, and no problem of introducing additional mode coupling will arise, provided the corresponding axes are either all parallel (two plates of the same handedness) or all antiparallel (two plates of opposite handedness).

Realization of acceleration compensation in the manner set forth in this paper requires the availability of quartz bars of both handednesses. Almost all of the cultured quartz Y-bars produced today are right-handed, although left-handed bars can be obtained on special order. For the purpose of making doubly rotated SC cuts in the same manner as AT cuts, it is possible to grow rotated Y-bars (SC-cut bars) by using a seed with length in the X'_2 direction, rotated by $\phi \approx 22^\circ$ about the X_3 axis [71], [72]. Line drawings of the resulting bars are shown in Figs. 6 and 7 for right-hand quartz; reflection in a mirror gives the left-handed enantiomorphs. Cultured quartz Y-bars ordinarily used for AT cuts can be used directly, in place of SC-bars, to make SC cuts [73]. The yield is approxi-

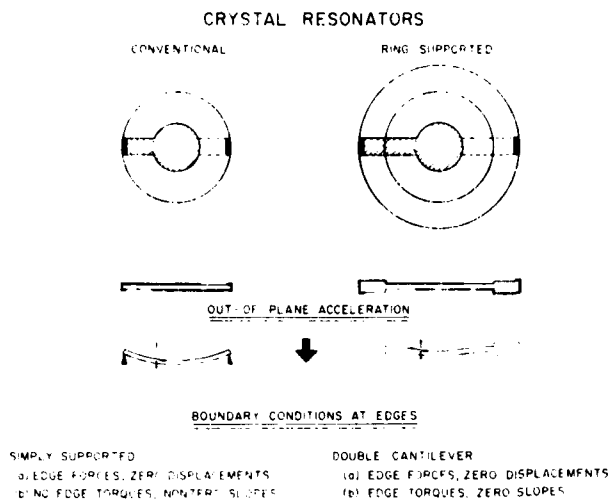


Fig. 8. Conventional and ring-supported crystal resonators, showing the effects of out-of-plane acceleration on each. The conventional resonator is subjected to simply supported boundary conditions at its edges, while the ring-supported resonator has double-cantilever edge conditions. Frequency shift is proportional to deformation at plate center, which is less for the ring-supported structure.

mately 30 percent higher than with the rotated SC-bar. This possibility is brought about by the threefold symmetry existing about the Z axis in quartz. A Y cut, for example, could be made by cutting perpendicular to the X_2 axis of a Y -bar. It could also be made by cutting perpendicular to either of the two other X_2 axes spaced around the X_3 axis at intervals of 120° . In either of the latter cases the area of the slices would be larger than that in the first case. In like manner, to produce SC cuts one could either rotate first around X_3 from X_1 by approximately 22° , then make the second rotation about the new X'_1 axis, or one could rotate $120^\circ + 22^\circ$, or $240^\circ + 22^\circ$ for the first rotation about X_3 . The second choice, namely, $\phi \approx 262^\circ$ produce a rotation that leaves the new X'_1 axis only about 8° ($270^\circ - 262^\circ$) from the original $-X_2$ axis. One is then nearly rotating about the length of the Y -bar for the second (Θ) rotation. (Because the $-X_2$ axis is involved, the sense of the Θ rotation is reversed.) Cutting in this fashion is thus nearly as efficient as cutting AT 's; one wants, however, to have the X_1 dimension as long as possible. At present, approximately 40 mm along X_3 is standard, and 75–100 mm along X_1 can be readily made.

In the foregoing we have seen that it is necessary for the corresponding axes of the quartz plates to be properly identified. In particular, it is advantageous to have a simple method of determining the positive and negative X_1 axes of blanks. One practical and simple method is to use chemical etching [74], [75]. For doubly rotated SC cuts it has been shown to be a readily applicable and practical method [75].

RING-SUPPORTED STRUCTURES

For accelerations out of the plane of the crystal plate, desensitization of acceleration-induced frequency shifts may be partially accomplished by use of ring-supported resonators as shown in Fig. 8 [36], [76]. The improvement comes about

by the alteration of the boundary conditions at the plate periphery as described at the bottom of Fig. 8. Frequency shift is proportional to deformation at the plate center, which is less for the ring-supported than the conventional resonator. When the acceleration is in the plane of the plate, one cannot make any *a priori* statements concerning the magnitude of the effect, except that it will depend on the azimuth angle of the acceleration field. The ring-supported resonator may be fabricated of any cut. The increased insensitivity of the SC cut over the AT , coupled with use of this structure, may provide sufficient acceleration immunity in certain applications, so that resonators of this type can be used individually. Beyond this, paired enantiomorphs, either discrete or stacked may be used. The inverted mesa structure [63], [77], [78] formed in the central region of the plate need not be plano-plano. Either plano-convex or biconvex forms are desirable alternatives [79], [80].

CONCLUSION

The balanced enantiomorphous structures described in this paper possess the advantage of admitting considerable variety in design and use. Some principal features permitted are the following:

- compensation for arbitrary acceleration directions;
- discrete or stacked resonator configurations;
- singly or doubly rotated cuts;
- special mounting systems:
 - BVA design [33], [35], [81], [82];
 - rhomboid resonators [16];
 - ring-supported resonators [36];
- any crystal in an enantiomorphous class;
- plano-plano, plano-convex, or biconvex plates;
- any mode type for which reversal of the acceleration field is found to reverse the frequency shift in a single resonator:
 - thickness bulk acoustic wave (BAW),
 - contour BAW,
 - flexure BAW,
 - surface acoustic wave (SAW),
 - shallow BAW (SBAW) or surface-skimming bulk wave (SSBW);
- series or parallel electrical connection,
- combinations of the foregoing.

For example, a possible combination consists of two ring-supported resonators, each having a plano-convex contour in the inverted mesa portion, stacked together with ring structures abutting.

Disadvantages of these combinations are the following:

- difficulty of bonding or joining plates in stacked structures (but see [64]);
- edge mountings of circular resonators are sensitive to small orientational errors [27], [29];
- stacking misorientation errors couple plate modes [42].

The composite resonator structures described in this paper may be modeled by means of equivalent networks introduced for this purpose and discussed in [1].

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