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NEW TRENDS IN QUARTZ RESONATORS DEVELOPMENTS AND APPLICATIONS

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Piezoelectric quartz crystal oscillators are present in almost any frequency control equipment. Under those conditions important efforts have been devoted to quartz resonators and oscillators everywhere in the world. Also demanding and important has been the development of new quartz piezoelectric sensors. Then, quartz crystal resonator is the "heart" of frequency standards and sensor equipments as well.

In this paper, quartz resonators are presented trying to provide important concepts for new developments and applications in the field.

A short historical review providing general ideas is first presented. Then, since recent progress in resonator understanding and design have lead to overcome most previous limitations, the last important advances are pointed out and discussed. Basically, late improvements are largely due either to better theoretical understanding or to improvements of boundary conditions. Both are presented. Consequences are doubly rotated crystals, use of a crystal on two or three frequencies. Boundary conditions at the limits of the vibrating body have to be paid a great deal of attention. This leads to some new designs which include "unelectroded" crystals and "quartz monolithic mount" of resonators.

Recent improvements in low aging, low external pressure variation sensitivity, fast warm-up are discussed in relation with different designs. Improvements of commercially available units are also presented according to several domains of application ranging from watch industry to high precision measurements.

In conclusion, some new developments and applications are pionted out.

Introduction and historical review

Principal milestones in piezoelectricity and its applications may be indicated as follows:

1880: Pierre and Jacques Curie, Discovery of piezoelectricity.
1893: Lord Kelvin, Microscopic theory of piezoelectricity in quartz crystal.
1910: Voigt, Lehrbuch der Kristall Physik.
1914–1918: Langevin, Work on ultrasonic detection in water.

1918: Nicholson (Bell Labs), Patent on oscillating circuit with Rochelle salt crystal (US Patent 2212845, April 10 1918).

1920: W. G. Cady Patent on oscillating cricuit with 3 vacuum tubes and quartz crystal resonator (in feed back circuit).

1921: Pierce's first oscillator.

1926: First crystal controlled radio station in New York city.

1939–1945: 130 millions of crystal resonators and oscillators were manufactured during world war II.

1948: Introduction of coated units by R. A. Sykes.

1952: Introduction of energy trapping by A. W. Warner.

1975: Doubly rotated SC cuts by E. P. Eernisse.

1975: Ceramic flat pack for resonators by Wilcox, Snow, Hafner and Vig.

1976: Electrodeless BVA resonator by R. J. Besson.

1980–1990: Important efforts to obtain ultrapure, dislocation free quartz material.

In fact, piezoelectric resonators are solids (plates, bars,) of a given configuration shape and dimensions prepared from high quality material under precise control of orientation. Geometric shape is fundamental since frequency depends on one or several dimensions of the vibrating solid which turns out to be a cavity for acoustic waves. Electrodes provide electric field but only certain vibrations are piezoelectrically driven. Electrodes can be deposited on crystal or they can be located very close to the crystal (so said "electrodeless" crystal). To summarize we have:

– a crystal solid vibrating according given modes and frequencies with a given quality factor,

– electrodes used to piezoelectrically drive vibrations and at the same time to detect vibrations. Classical distinction between bulk acoustic waves and surface acoustic waves has of course to be made (in this paper B.A.W. devices will rather be considered).

Notice:

– for resonators used in frequency control, a particular interest is devoted to frequency variations versus temperature. Actually, the user looks for turn over temperatures which provide the working points of the temperature controlled ovens.

– frequency may depend and actually depend on various external parameters (temperature, pressure, acceleration, force etc). The resonator can be made to be sensitive in frequency dependance, then it is used as a sensor.

The first piezoelectric resonators were used by Langevin, Nicholson and Cady. Cady's resonator was invented in 1920 giving rise to fabrication at artisan rate until second world war. Electrodes were not deposited on the crystal but technology could not take advantage of it. Between 1944 and 1948, R. A. Sykes introduced electrodes deposited on the crystal and in 1952, A. W. Warner introduced energy trapping. The Warner's technique is still used nowadays without any major change. After 1975 doubly rotated cuts began to be used following recommandations of Eernisse, Ballato and Besançon's group. These doubly rotated cuts had more or less been previewed since 1938 and they could overcome some limitations of the regular *AT* cut Warner's resonator. In the last fifteen years several new resonators have been introduced (BVA resonators, flat pack, resonators, miniature resonators, composite resonators, UHF resonators and so on).

In fact, quartz oscillators are present in almost any time or frequency control equipment. Piezoelectric sensors are widely used especially as precision sensors. As a consequence tremendous effort has been made towards better piezoelectric resonators especially during the two last decades. Recent progress in resonator understanding and design leads to overcome most previous limitations. As a result, a single crystal oscillator can now provide, at the same time, excellent short term stability and excellent long term drift. Fast warm-up can be obtained together with other excellent characteristics. Also impressive (and necessary) is the achievement of very small g sensitivity (less than $10^{-10}/g$).

Improvements of piezoelectric resonators is particulary necessary for lower aging, better thermal stability, lower thermal transients and lower environmental dependence (vibration shock, acceleration, radiations). Basically, improvements could come from efforts in many domains (better theory, better or new piezoelectric material, better design, better processing. In fact, late improvements are largely due either to better theoretical understanding or to better consideration and achievement of boundary conditions. Both lead to new concepts and new design yielding better short term stability, aging rates, thermal characteristics, g and new environmental sensitivities. Also due to passive methods [1], [2] improvements on resonator alone can be clearly seen. In addition may be time for new concepts in resonator design.

In fact, for somebody who is not too much impressed by the extraordinary amount of available literature on resonators, each step of the resonator design can be reconsidered. This sometimes arises questions which, at first, look almost childish. For example:

Why do crystals have usually circular or rectangular shapes and spherical contours?

The answer is that quartz does not care but it is usually easier to deal with those shapes and contours. If correctly handled this interrogation can lead to interesting new shapes or contours. Technical feasibility or (and) even tradition often determines the fabrication method. In addition, it is so delicate to make excellent resonators that the slightest change can be critical. This does not encourage the use of new concepts; it promotes the advantages of established procedures. But, theoretical understanding has been considerably improved and technology has fast evolved. In other words, important further advances are still possible and probable. But this will be very difficult. Part of the problem is that every step of the fabrication proces has to be excellent; any failure anywhere can mask an improvement nevertheless achieved. To begin with, improvement of the material quality is slow and difficult though very impressive effort is made in that domain and quartz material is not challenged in many applications.

1. Brief presentation of quartz crystal resonators

The resonator outlined in previous section may be represented on Fig. 1. Question marks show the main points of interest and sources of difficulties for crystal manufacturers. Of importance is the fact that the external world unfortunately is a source of vibrations, accelerations, temperature and pressure variations.

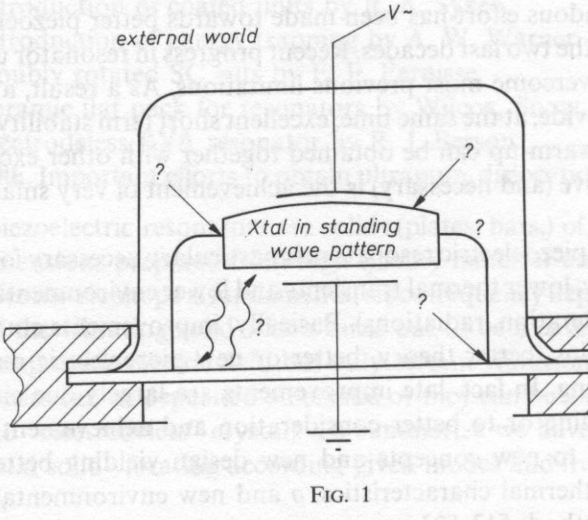


FIG. 1

The usual equivalent circuit of Fig. 2 is valid around a resonant frequency. The intrinsic Q_i factor of a resonator is given by:

$$Q_i = \frac{\bar{c}}{\omega \eta_s}$$

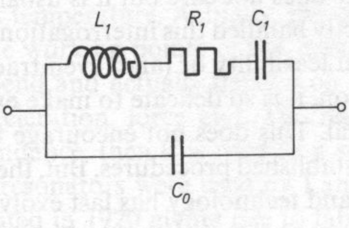


FIG. 2

where c is the rotated elastic coefficient (piezoelectric effect included) η_s is the viscosity constant.

In fact, the previous formula assumes a perfect resonator and Q_i represents an upper limit since the actual Q factor Q_a is given by:

$$\frac{1}{Q_a} = \frac{1}{Q_i} + \frac{1}{Q_1} + \frac{1}{Q_2} + \ldots + \frac{1}{Q_n}$$

where the Q_n each correspond to a particular phenomenon increasing damping (acoustic losses through fixations, mass loading losses in the surface layers, losses due to imperfections, dislocations, impurities and so on).

Then the quality factor Q_a of an actual resonator depends:

– on the intrinsic Q_i, i.e., on the actual cut, frequency and η_s (a *BT* cut basically yields 2.3 times the Q factor of an *AT* cut),

– on the construction of the resonator (ideally on would aim to obtain one single resonant frequency only and introduce no other losses than material losses).

The crystal manufacturer is usually very careful checking the following:

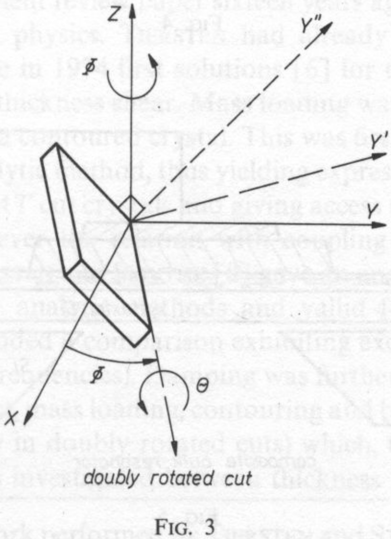
a) *Frequency temperature behaviour*

For a bulk resonator high frequency thickness shear vibrating the frequency f at a temperature T between $-200°$C and $+200°$ C is given by

$$\frac{f - f_0}{f_0} = a(T - T_0) + b(T - T_0)^2 + c(T - T_0)^3$$

where $f = f_0$ for $T = T_c$.

a, b, c are functions of the rotated material constants for a given mode of vibration.



doubly rotated cut

FIG. 3

The singly rotated AT cut (C mode vibrating) is one for which: $a = b = 0$. This cut will provide us with an interesting behaviour versus temperature since two "turn over" points are available on the plot of frequency versus temperature thus giving rise to temperature stabilization. Let us assume now that additional interesting properties are needed. For instance minimal nonlinear effects or independence versus stresses in the plane of the cut are desired. One more degree of freedom must be used thus leading to doubly rotated cuts of Fig. 3. Singly rotated cuts correspond to $\Phi = 0$.

Similar considerations to those developed for bulk resonators can be developed for S.A.W. devices and give very promising cuts as a result.

b) *Modes of motion*

If the crystal vibrates, the corresponding waves propagate and may form standing wave patterns for given frequencies. The corresponding patterns are called resonance of motion. Complete understanding and investigation of those modes are needed for any improvement in quartz crystal design. Usually, the radiofrequency spectrum of a reso-

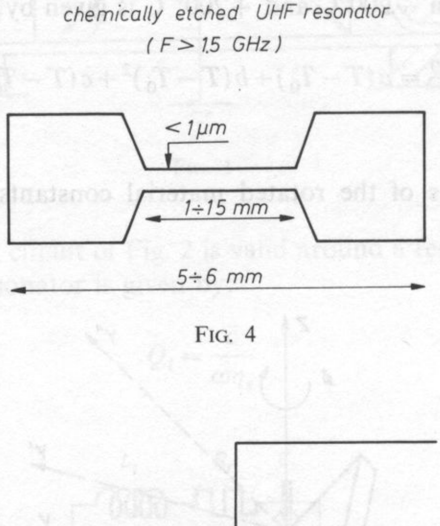


FIG. 4

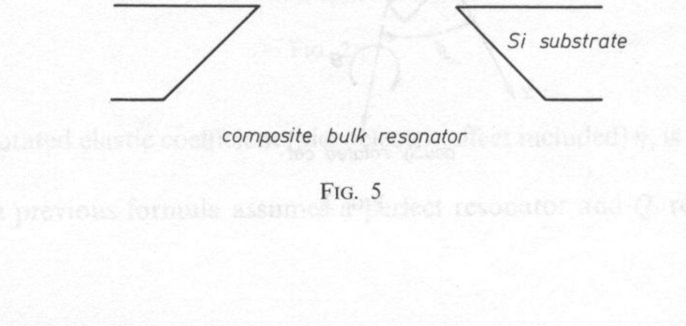


FIG. 5

nator is very complicated (but still does not comprise vibrations which do not give rise to an electric resonance) and its complete investigation needs theoretical developments, together with accurate analysis by *X*-ray topography scanning electron microscopy interferometry, holography or so.

Before going to more details it is important to point out the extraordinary large variety of crystal resonators. In fact, the piezoelectric resonator domain has been considerably extended for example to watch miniature crystals, UHF resonators for the GHz range (Fig. 4 shows such a crystal chemically etched) or composite bulk resonators (Fig. 5).

Also important is the fact that last two decades improvements have really been tremendous. This will be discussed in the next sections.

2. Resonator understanding together with theory verification is most important and fruitful

A. Better theoretical understanding of resonator have brought in many results during the last decade

A pointed out [3] by Pr. V. E. BOTTOM, one problem, in the quartz crystal business, has been, in the past, a relative lack of research and development together with difficulties for piezoelectricity to be part of programs in Schools of Electrical Engineering. However, the last decade has brought out important advances in fundamental understanding of piezoelectric resonators. We will try to give some examples in the next sections.

1. Analysis of the vibration from a three dimensional point of view. As pointed out by HAFNER [4] in his excellent review paper sixteen years ago, the subject is one of the most difficult in classical physics. TIERSTEN had already indicated many ways to solution [5] when he gave in 1974 first solutions [6] for trapped energy resonators operating in overtones of thickness shear. Mass loading was already involved but not the radius of curvature of a contoured crystal. This was first proposed by WILSON [7] using an approximate analytic method, thus yielding expressions for overtine frequencies and displacements in *AT* cut crystals and giving access to comparison with X rays Lang's topographs. However the relation with coupling between modes was not investigated. In 1977, TIERSTEN and SMYTHE [8] gave an analytic solution introducing contour and coupling by analytic methods and vallid for *AT*-cut quartz crystal resonators (the paper included a comparison exhibiting excellent agreement between calculated and measured frequencies). Damping was further introduced in 1978 using [9] Tiersten's model. In fact, mass loading, contouring and boundary conditions imply coupling effects (especially in doubly rotated cuts) which, then, have to be studied.

— Coupling has been investigated between thickness modes themselves

This was the case of work performed by TIERSTEN and STEVENS [10], [11] using an analytic method which replace mechanical displacement by its decomposition on the eigenvectors triad of Christoffel's problem. This was also the case of work done by BOURQUIN [12] using an analytic method and by DULMET [13] using a semi-analytic perturbation method valid for *AT* and *SC* cuts. Later improvement by introduction of temperature was performed and was presented in 1984 [14] leading to effects of coupling on frequency spectrum and frequency versus temperature behaviour of counteres resonators. The improvement is obtained through use of "effective elastic coefficients" introduced by BOURQUIN and DULMET [15], [16], [17]. It turns out that influence of the choice of the state of reference on temperature coefficients of elastic coefficients is very important. Finally, an interesting special case has been investigated and presented recently [18]. Strong coupling arising from modes having close frequencies and different thermal sensitivities is investigated thus giving one possible mechanism for certain "accidents" occuring on frequency versus temperature curves (Fig. 6).

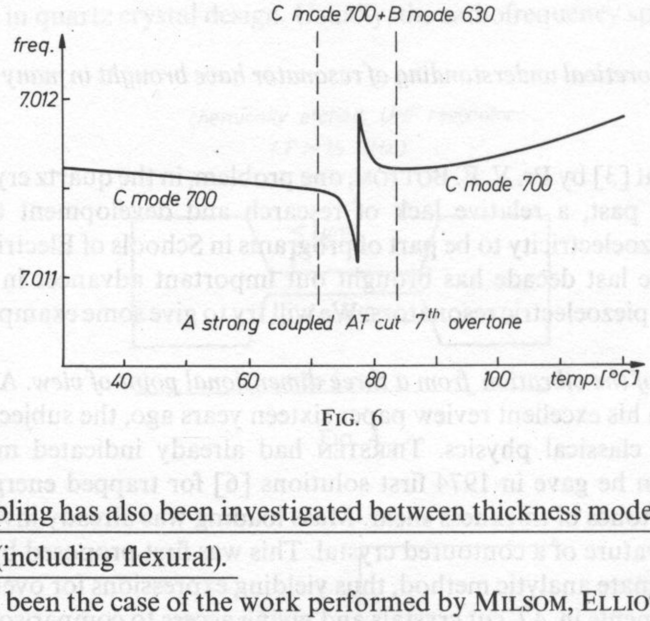


FIG. 6

— Coupling has also been investigated between thickness modes and other kinds of vibration (including flexural).

This has been the case of the work performed by MILSOM, ELLIOTT and REDWOOD [19]. (This three dimensional theory adresses miniature resonators, uses a perturbation method and utilises complex wave numbers). Coupling between thickness modes and other modes is also largely investigated by MINDLIN and his disciples (using Mindlin's special method) [20], [21], [22].

It is to be pointed out that ref. [22] by LEE and YONG adresses doubly rotated plates and shows how frequency temperature behaviour is affected by plate dimensions and orientations.

As a conclusion: it can be said that tremendous advance has been made in the analysis of the vibration from a three dimensional point of view. In our opinion, further improvements should come from including edge boundary conditions which have not been considered except for choice of mounting points or calculations of force-frequency constants for example by BALLATO [23], [24].

2. *Lagrangian formulation and temperature problems.* This formulation and been extensively used in the analysis of the influence of static stresses on the resonant frequency. It is also very useful to study non linearities such as amplitude frequency effect [25], [26], [27], [28].

This was first done in order to reduce sensitivities to forces and accelerations or in order to make force sensors or accelerometers. A good example is the calculation by LEE and KUANG-MING WU of the effects of acceleration in AT cuts or doubly rotated plates [29], [30]. The method was also used to determine thermal sensitivities either as dynamic temperature variations or as static temperature variations.

<u>Static temperature variations.</u>

Much work has been done in this domain especially by LEE and YONG [31] using material from previous work [32]. It is also used in the case of the stress free temperature variations [15]. In a classical manner, vibration of a resonator by referen-

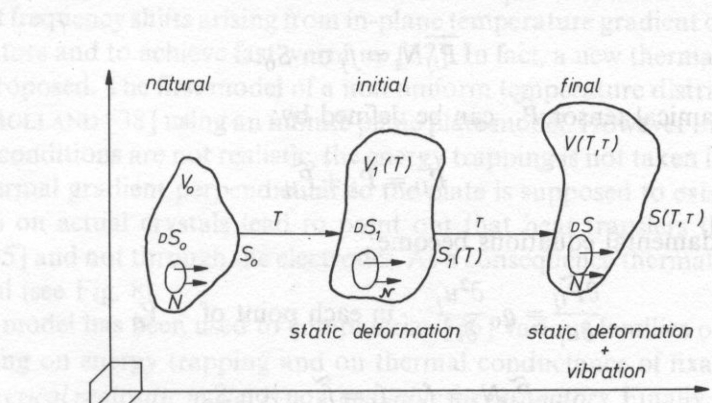


FIG. 7

ce to the 3 states of a solid Fig. 7 is obtained by use of the following equations of equillibrium and boundary conditions:

$$\frac{\partial \tau_{ij}}{\partial x_i} = \frac{\partial^2_{uj}}{\partial t^2}, \text{ in each point of } V \tag{1}$$

$$\tau_{ij} n_i = f_j, \text{ in each point of } S \tag{2}$$

with

$$\tau_{ij} = B_{ijkl}\frac{\partial u_k}{\partial x_l} \tag{3}$$

where τ_{ij} is the usual stress in the final state, n_i is the direction cosine of surface element dS and f_j the external force applied on dS.

It is clear that ϱ and n_i depend on static deformation and therefore on temperature. But important advantage can be obtained using the a_i coordinates [25] as independent variables. Equations corresponding to Eq(1) and Eq(2) then make use of Piola tensor P_{ij} [25]:

$$P_{ij}N_i dS_0 = \tau_{ij} \tag{4}$$

where N_i is the direction cosines of dS_0. P_{ij} tensor corresponds to total deformation (static deformation with thermal origin plus dynamical deformation). Without dynamical deformation we obtain the static Piola tensor $\overline{P_{ij}}$:

$$\frac{\partial \overline{P_{ij}}}{\partial a_i} = 0 \quad \text{in each point} \quad V_0 \tag{5}$$

$$\overline{P_{ij}}N_i = f_j \text{ on } S_0. \tag{6}$$

In fact a dynamical tensor $\widetilde{P_{ij}}$ can be defined by:

$$P_{ij} = \overline{P_{ij}} + \widetilde{P_{ij}}. \tag{7}$$

Then the fundamental equations become:

$$\frac{\partial \widetilde{P_{ij}}}{\partial a_i} = \varrho_0 \frac{\partial^2 u_j}{\partial t^2} \quad \text{in each point of} \quad V_0 \tag{8}$$

$$\widetilde{P_{ij}}N_i = f_j - \overline{f_j} = \widetilde{f_j} \quad \text{on } S_0. \tag{9}$$

It can be easily seen that $\widetilde{P_{ij}}$ can be expressed by:

$$\widetilde{P_{ij}} = A_{ijkl}\frac{\partial u_l}{\partial a_k} + \frac{\varrho_0}{\varrho_1}\frac{\partial a_k}{\partial x_l}\frac{\partial a_i}{\partial x_m}\overline{T}_{ml}\frac{\partial u_j}{\partial a_k} \tag{10}$$

where $\overline{T_{ml}}$ represents mechanical stress without vibrations ($u_i = 0$). A_{ijkl} is a tensor of elastic coefficients. If the resonator is free to expand without induced stresses, $\overline{f_j}$ and $\overline{T_{ml}}$ are zero in any point of the solid. Then:

$$\widetilde{P_{ij}} = A_{ijkl}\frac{\partial u_k}{\partial a_l} \tag{11}$$

A_{ijkl} defines new coefficients so called "effective elastic coefficients".

Let us point out advantages obtained by use of those effective coefficients. In fact, everything is refered to a so said "natural state" at the reference temperature To including propagation equation and boundary conditions. This finally turns out to be simpler and at the same time more accurate. For instance, the slight change in orientation due to temperature or the fact that a sphere expands into an ellipsoid are taken into account. This can be of importance especially in the case of some doubly rotated cuts as RT cuts. Finally this method entitles to separate dimensional variation of resonator due to temperature from variations of elastic coefficients with temperature. In other words a fictive medium without expansion is considered but its mechanical coefficients have (compared to the actual medium) a different variation with temperature.

Dynamic temperature variations.

Much work has been performed in that domain especially by TIERSTEN, STEVENS and SINHA [33], [34]. It is to be pointed out that the case of doubly rotated cuts is included. Another important advance was recently introduced by VALENTIN [35] and used to predict frequency shifts arising from in-plane temperature gradient distribution [36] in resonators and to achieve fast warm up [37]. In fact, a new thermal model for resonator is proposed. The first model of a non uniform temperature distribution was proposed by HOLLAND [38] using an infinite plane plate model. However in this model the boundary conditions are not realistic, the energy trapping is not taken ino account and only a thermal gradient perpendicular to the plate is supposed to exist. Realistic considerations on actual crystals lead to point out that heat transfers through the quartz itself [35] and not through the electrodes. As a consequence thermal gradient is basically radial (see Fig. 8).

This new model has been used to computerize [36] various families of isotherms either depending on energy trapping and on thermal conductance of fixations.

3. *A theoretical realisatic model is now available for resonators.* Finally, during the last decade three dimensional models for analysis of the vibration were progressively made available taking contour and coupling into account. Almost any characteristic of a resonator can now be computed from its parameters. The effect of static and dynamic temperature variations can be accurately predicted. A new thermal model far from the infinite plane plate is also available. In other words, in every domain, theoretical models are much more realistic and differ from the old infinite plane plate model which however is the basic of determination of mechanical coefficients C_{ij} and their temperature coefficients. It would probably be interesting to remarke the experiments of BECHMANN, BALLATO, and LUKASZEK [39] using accurate energy trapping models to redetermine some coefficients and their derivatives by respect to temperature. (In fact, improvements in accuracy of these coefficients are now needed to define new cuts or design new resonators and sensors).

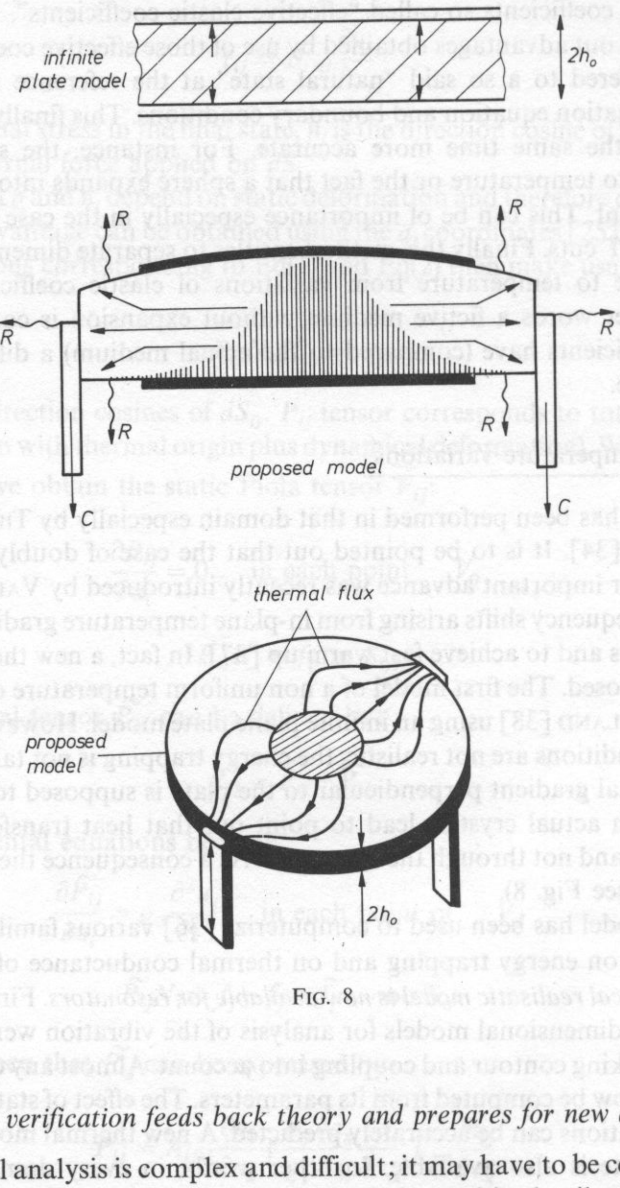


FIG. 8

B. Theory verification feeds back theory and prepares for new designs

Theoretical analysis is complex and difficult; it may have to be completed by finite elements techniques but it always has to be confronted in detail with actual figures. Various diagnostics and measurements have to be performed at each step of fabrication (on raw material, water, surface, interface, fixation, electrode, deposition, cleaning, enclosing, and on final resonator). For simplicity, only visualization of crystal's vibrations will be considered here.

1. X *ray topographic techniques.* When an actual resonator has been designed, it is possible to get, from theory, every resonant frequency with it's associated vibration pattern, in the whole needed frequency domain. Then, the actual resonant frequencies

and vibration patterns have to be obtained, for instance, through Lang's or similar X ray topographic techniques [40]. Though many exciting new results can still be found in that field, the technique is now well known. It needs very well trained people using expensive equipment. However, even if is time consuming there is no way properly design a new resonator such a technique (or a similar one). On the pattern of Fig. 9, theoretical results and topographs appear at the same time. The engineer and the theoretician need to discuss for design evolution trying to avoid or explain unexpected patterns. The technique can also be used for study of coupling between modes under variation of temperature provided an adequate oven transparent to X rays is used [18].

2. *Other techniques.* Many other techniques have been used recently to visualize or computerize actual vibration patterns. This is the case in laser interferometric measurement of vibration displacements [41] or in measurements using speckle effects [42].

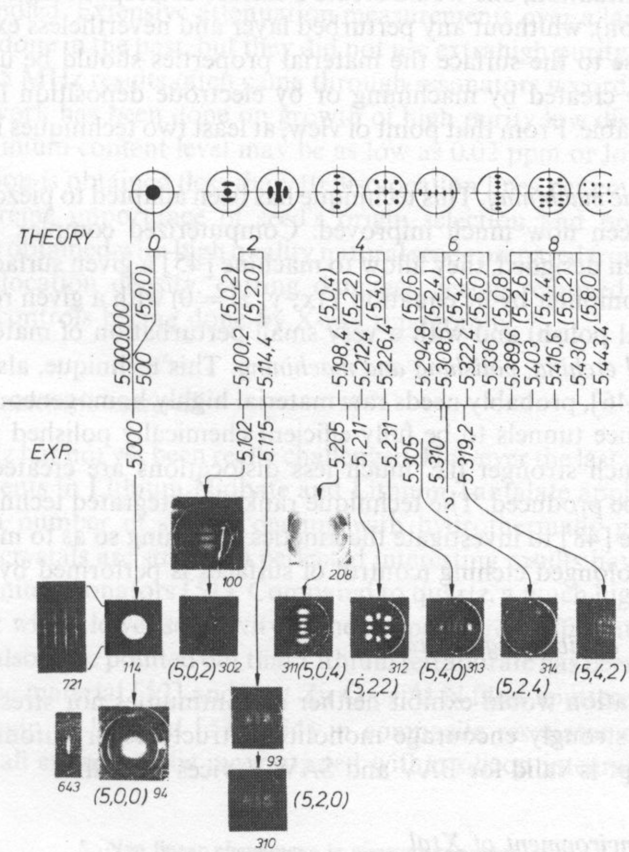


FIG. 9

3. Better consideration and achievement of boundary conditions

A crystal resonator is a solid limited by surfaces connected to outside changing world by fixations, electrodes and surrounding medium (Fig. 1). Interactions are mechanical and thermal and electric. Obviously boundary conditions have to be paid a great deal of attention and care [43], [44]. Important improvements are still ahead.

As we have seen in Sect. 2, theory now includes much more realistic boundary conditions. But also new techniques are developed with much better achievement of surface limits, much better mounting of piezoelectric crystal. Some examples will be considered here.

A. Surface of piezoelectric medium

In an ideal situation, one would create a surface corresponding exactly to a given shape (or equation), whithout any perturbed layer and nevertheless exhibiting optical polish. Very close to the surface the material properties should be unperturbed. No defect should be created by machining or by electrode deposition i.e. "electrodess" crystals are desirable. From that point of view, at least two techniques have been found promisive.

1. *Ultrasonic machining.* This technique has been adapted to piezoelectric crystals [43] and has been now much improved. Computerized complex U.S. machining systems have been designed, they allow to machine [45] a given surface even complex (introduced in computer by its equation $f(x, y, z) = 0$) with a given roughness (down to almost optical polish) and with a very small perturbation of material properties.

2. *Chemical etching, polishing and machining.* This technique, also introduced in the last decade [46], probably needs raw material highly homogeneous without given defects for instance tunnels to be fully efficient chemically polished [47] blanks are mechanically much stronger (i.e. much less dislocations are created) and complex geometries can be produced. The technique ranks in integrated techniques and much effort is still done [48] to investigate the kinetics of etching so as to master changes of surfaces with prolonged etching (control of surfaces is performed by S.E.M.).

B. Fixation of vibrating crystal

An ideal fixation would exhibit neither discontinuities nor stresses nor changes with time. This strongly encourage monolithic structures or automounted crystals [43]. The concept is valid for BAV and SAW devices as well.

C. Direct environment of Xtal

Last decade has seen continuing improvement in cleanliness of crystal, processing, including single step high vacuum processing bake out and sealing and U.V. cleaning procedures. Coldweld sealed metal enclosures and ceramic hermetic flatpacks have been developed for similar purposes.

4. Improvement in the "quality" of piezoelectric material is still needed

Recent improvements in resonator understanding and technique, radiation hardening requirements are strongly boosting research and development for "better" piezoelectric material. Better may also mean better availability and continuity in the supply of a given quality of material. Also, piezoelectric material suppliers have to consider industrial yield and this does not always encourage for highest quality material because the market may be too small.

A. Quality of quartz material

For those who work on the forefront of piezoelectric devices, availability of excellent material is still a problem. Nobody really knows where would be the limits of ultra high purity quartz with very few dislocations and growth defects, if that material was properly handled. Extensive attenuation measurements over a large temperature range have been done in the past, but they did not use extrahigh purity dislocation free material (and at 5 MHz results often came through resonators according to Warner's design). Recent work has been done on growth of high purity low dislocation quartz [49], [50]. Aluminium content level may be as low as 0.02 ppm or lower and a large degree of perfection is obtained (less than 10 disolocation lines per cm^2). Experiments demonstrate extreme importance of seed's origin selection and preparation. Best results seem to be obtained with high quality natural seeds prepared from areas selected for very low dislocation density, cutting damages beeing removed from the seed surfaces and all controls beeing done by X-ray topography.

B. New piezoelectric material

In fact, quartz has not yet been really challenged. However the last decade has seen further developments in Lithium Niobate and Lithium Tantalate applications. It has also seen quite a number of studies dealing with hydrothermally grown Berlinite crystals. Though crystals are still to be perfected interesting results have already been obtained on Berlinite resonators [51]. Compared to quartz, a much higher coupling is obtained together with a lower sensitivity of the temperature coefficients of frequency.

Finally, it is also to be pointed out that Lithium tetraborate has been introduced as a new piezoelectric material [52] and that Zn O or Al N films sputtered on to simple crystal Silicon begin to be used [53], [54] in composite resonator structures. The structures are small enough to be incorporated within silicon integrated circuits.

5. Non linear phenomena in quartz resonators

Several properties of resonators strongly depend on non linearities of quartz material. Harmonic generation, amplitude frequency effects and intermodulation correspond to propagation of a finite amplitude wave in a non linear medium. Sensitivities to external or internal perturbations (temperature, force, pressure acceleration electric field) are due to the coupling between the high frequency wave and the non linear strained medium: they deserve a non linear treatment.

Fifteen years ago some non linear coefficients were still needed when measured by the author [55] to explain non linear effects in quartz resonators [56]. However it is clear that, to day, some important advances in the resonator field are due to success in non linear effects study and handling. Detailed information will be found in Ref. [56] or in a recent review paper [57] which also calls attention on the concept of lattice waves and phonons (leading to description of thermal conductivity) thermal expansion and acoustic attenuation by means of phonons interactions).

An interesting new non-linear analysis method has also been recently proposed [58] and caused to find out both theoretically and experimentally a so called "non-rationnal frequency division" [59].

The important part of the *SC* cut resonator is also to be pointed out in that field since amplitude frequency effect, intermodulation sensitivity to planar stresses are much reduced [57] [60].

Recently frequency and phase noise in quartz resonators have been studied [61] as a function of the driving power. At low power $1/f$ fluctuations are observed but at medium power (some mw) the non linearities of the crystal increase the phase fluctuations when at high powers thermal instabilities and chaotic behaviour occur (together with high level white noise).

6. Evolution in resonator or sensor design. New concepts

In this section, some advances of the last decade will be recalled. To begin with, the importance of effective production of doubly rotated thickness mode plates will be pointed out. Though introduced before world war II, doubly rotated resonators have really been developed after work by EERNISSE [62], [63] on *SC* cuts. In this paper we will basically refer to the exhaustive paper by BALLATO [64] and point out the exceptionnal advantages of doubly rotated plates (in particular for *SC* or *TTC* cuts, low sensitivities to stresses in cut's plane, excellent thermal behaviour including thermal transient [65] and low amplitude frequency effect [66]). This is the reason why intensive efforts on doubly rotated crystals have been reported during the five last years causing doubly rotated plates to be, now, commercially available.

Some new resonators or new concepts that appeared in the last decade will now be rapidly presented:

A. New resonators or techniques

1. Ceramic flat pack resonators [67], [68], [69], [70]. As pointed out by several authors, usual packaging techniques do not insure hermeticity thus exposing the crystal to contamination. The ceramic flat pack technique uses ceramic material together with aluminium gaskets and allows mass production. This new configuration yields a small, highly reliable rugged crystal (polyimide bonding cans be used).

2. BVA techniques. This technique was introduced in Besançon, France, after 1975 [43], [44], [71], [72]. It is now well known and industrially produced [73], [74] though many models described are not yet in production line. The new BVA_n structures may use a rather conventionnal bonding and a special fixation (n odd) or may use "automounted" crystals i.e. crystal with monolithic fixations made out of quartz (n even). The crystals are usually "electrodeless" but electrodes can also be deposited on vibrating crystal (patent n° 77 17 309) so leading to BVA_4 or QAS designs [74]. Fig. 10 recalls some of the different designs proposed.

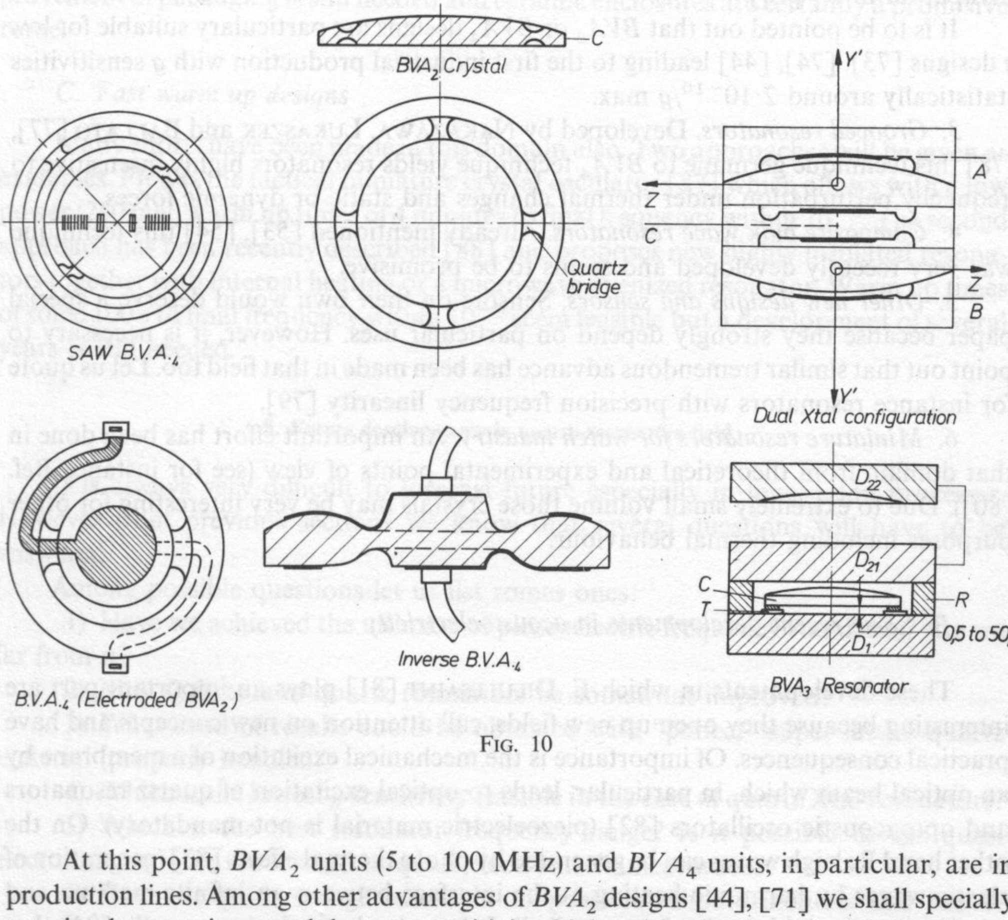


FIG. 10

At this point, BVA_2 units (5 to 100 MHz) and BVA_4 units, in particular, are in production lines. Among other advantages of BVA_2 designs [44], [71] we shall specially mention lower aging, much lower g sensitivity, higher drive levels and existence of zero aging drive levels [75]. More precisely, BVA_2 resonator allow much higher drive levels without degrading badly drift rates. Moreover theoretical considerations and experimental data [75] show that resulting aging a_r may be, as a first approximation, modeled by:

$$a_r = a_i + kP\{1 + a\exp(-\sqrt{P/P_0}\,t/\tau) + \ \dots\}$$

where: a_i is an intrinsic aging depending on material and cut, k is a constant depending on material and cut, a is a constant without dimension, P is the power dissipated in motional resistance R_1, P_0 is a reference power level, τ is a time constant; t is time.

This formula shows evidence of a drive level P_1 yielding on aging rate crossing zero. For natural Brazil quartz 5 MHz fifth overtone resonator P_1 is about 80 μw; 5 MHz third overtone *SC* correspond to 160 μw.

Using very high drive levels it is possible to "internally heat" the crystal by energy dissipation in R_1 [76].

It is to be pointed out that BVA_2 or BVA_4 designs are particulary suitable for low g designs [73], [74], [44] leading to the first industrial production with g sensitivities statistically around $2 \cdot 10^{-10}/g$ max.

3. Grooved resonators. Developed by Nakazawa, Lukaszek and Ballato [77], [78] this technique germane to BVA_4 technique yields resonators highly insensitive to frequency perturbation under thermal changes and static or dynamic forces.

4. Composite bulk wave resonators. Already mentioned [53], [54] this technique was very recently developed and seems to be promisive.

5. Other new designs and sensors. Sensors on their own would deserve a special paper because they strongly depend on particular uses. However, it is necessary to point out that similar tremendous advance has been made in that field too. Let us quote for instance resonators with precision frequency linearity [79].

6. Miniature resonators for watch industry. An important effort has been done in that domain from theoretical and experimental points of view (see for instance Ref. [80]). Due to extremely small volume those crystals may be very interesting for other purposes including thermal behaviour.

B. Some recent developments in acoustoelectricity

These developments in which E. Dieulesaint [81] plays an important part are interesting because they open up new fields, call attention on new concepts and have practical consequences. Of importance is the mechanical excitation of a membrane by an optical beam which, in particular, leads to optical excitation of quartz resonators and optoacoustic oscillators [82] (piezoelectric material is not mandatory). On the other hand Raleigh waves can be generated by photo thermal effects [83] (generation of elastic waves by harmonic heating at the interface between an infinite medium and a backing material has also been studied). It has also been shown recently [84] that Lamb waves can be launched in glass plates and detected by bulk wave resonators placed between the arms of tongs.

7. Recent improvements of resonators in relation relation with different designs

A. Low a designs

This subject has already been investigated by many authors and in particular in France [85], [86]. The author simply stresses that the models described in reference [85] do yield low *g* sensitivities.

B. Reducing aging

This is certainly one of the most difficult subjects. However the efforts during the last decade have finally yielded a reduction of an order of magnitude. BVA_2 design provide lower aging rate and final aging established within days. Nevertheless improvement of packaging is still needed and ceramic enclosures are certainly a promisive route.

C. Fast warm up designs

Many efforts have been made in this domain also. Two approaches will be given as examples. First is the tactical miniature crystal oscillator [87] which allows with a low power (250 mw) warm up times of 4 minutes to final frequency within 10^{-8}. The second approach has been recently described [88] and proposes new highly insulated resonators together with internal heating or a microwave ovenized resonator. Warm up times of some 100 s to final frequency within 10^{-9} seem feasible but a development of several years is still needed.

8. Future developments in quartz resonators field

It is always very difficult to forecast future especially in innovation processes. However from previous sections we know that several questions will have to be answered.

Among possible questions let us list somes ones:

1) Have we achieved the ultimate of piezoelectric frequency standards? Are we far from it?

2) May *Q* factors of quartz resonators be somewhat improved?

3) What kind of results could be obtained with "perfect" super lattice quartz material (properly handled)?

4) Which is the lowest *g* sensitivity feasible in the case of quartz Xtal resonators?

5) Which is the best resonator frequency range? Is it possible to use quasi electromagnetic waves instead of quasi electromechanical waves?

6) Have we paid enough attention to possible miniaturizations and use of monolithic structures?

7) Is energy trapping by spherical contours an optimal design?

8) Has resonator edge to be circular or rectangular?

9) Are nanotechnologies (in the Å range) of some use in quartz resonator design?

10) What is the future of non piezoelectric material for resonator design?

Of course some important questions are also related to the proper use of a resonator i.e. oscillator design theory and achievement.

One of the problems already pointed out is that there is not enough connection between the three trades involved in quartz oscillators achievement (i.e. material field, resonator field, electronics). Matching crystal to oscillator (or the reverse) is a very important task for success. Also oscillator design now benefits from computer aided design and various improvements including surface mounted components use and several others. Of course influences humidity have to be eliminated [89] through hermetically sealing (this also helps'emilinating pressure variations influence).

9. Conclusion: possible future trends (next 10 years)

Thanks to progress in resonator and oscillator fields as well, small, low cost, low consumption and rugged quartz oscillators or sensors are now available. Progress has yielded reduced aging, better short term stability, low thermal transient and small environmental dependance. Following table compares performances obtained 10 years ago with performances available to day for commercial precision crystals. From research area possible trands for near future are foreseen.

If we try tu summarize all the data obtained in the last 20 years, it is clear that 2 characteristics, aging and g sensitivity of oscillators, have been in constant progress while $\sigma_y(\tau)$ seemed to somewhat reach a limit in the vicinity of $7 \cdot 10^{-14}/10$ s at 5 MHz. Is is hard to predict what would happen with much better Q factors because it may depend on the type of Xtal (there is some evidence that part of the noise is correlated to proccesses in adhering electrodes) and obviously we still have to clear up various influences on noise processes (though in principle $\sigma_y(\tau)$ should vary as $1/Q^2$).

Some more confidence can be paid to improving and g sensitivity. An aging rate in the of $5 \cdot 10^{-11}$/year to $5 \cdot 10^{-10}$/year is probably in a reaching distance while a g sensitivity in the $10^{-11}/g$ range or better is probably achievable. Of course, such a low g sensitivity will also influence other parameters since an oscillator is never in a perfect mechanical environment. In other words we should see some more of the competition between high quality quartz standards and atomic rubidium references.

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Table 1.
(Commercial precision units)

	10 years ago	Now	Less than 10 years from now
$\sigma_y(\tau)$ 1s, 10 s	$4\ 10^{-13}$ to 10^{-12}	1 to $4\ 10^{-13}$	5 to 10×10^{-14}
Aging/year	2 to $3\ 10^{-8}$	3 to $6\ 10^{-9}$	5 to $9\ 10^{-10}$ predictible
g sens. max	$2\ 10^{-9}/g$	$3\ 10^{-10}/g$	4 to $7\ 10^{-11}/g$ SC 7 to $30\ 10^{-11}/g$ AT