DESIGN OF SC CUT 10 MHZ H.Q. CRYSTALS WITH G. SENSITIVITY BETTER THAN 2.10^{-10}/G.

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ABSTRACT

Several theoretical and experimental studies on the force-frequency effect have shown that the g sensitivity of a crystal resonator is directly related to the location and structure of the mounting support.

Our work has lead to the definition of a new design of crystal resonator having low sensitivity. The effects of both surface and body forces applied to the vibrating part of the crystal must be considered.

In this paper, the details of this new design are presented.

Statistical results show that g sensitivity between 3.10^{-11}/g and 2.10^{-10}/g on the worst axis are currently obtained on an industrial basis.

These values are measured by a 2 g tip over test in all directions either with Phase Modulated Reflectometer (which are also described at 5 and 10 MHz) or in classical oscillators.

INTRODUCTION

In numerous fields of the aerospace industry for communications, localization ... the needs of highly stable crystal oscillators has continually increased in quality as well as in performances.

In an hostile and vibration environment, the full potential of many systems is severely limited by the acceleration sensitivity of the resonator.

The search of g sensitivity lower than $3.10^{-10}/g$ and a high spectral purity of oscillator required by some modern applications leads to the development of new manufacturing processes which involve high technologies such as SC cut, ultrasonic machining, ultra high vaccuum...

The first theoretical approach of the acceleration sensitivity was presented by Lee and Kuang Ming Wu in 1976./ 2 /

At the same time, this problem was investigated by Valdois, Janiaud, Gagnepain. / 1, 5, 7 /

The force frequency effect is also of interest when dealing with g sensitivity of crystals resonators.

The first theoretical explanation of the force frequency effect was presented by PCY Lee Wang and Markenscof . They use an isotropic assumption for the determination of the plane stress distribution induced by the mounting support of a plate submitted to in-plane acceleration. Their results, given for AT cut, were in good agreement with the experimental values.

A more precise solution making allowance for the anisotropy of crystal was given by Ballato EerNisse and Lukasek. This study was applied to doubly rotated quartz resonator./ 4 /

Nevertheless, even if some of the phenomenon implicated in g sensitivity have been extensively described, there are not yet many crystal resonators which have been demonstrated with a low g sensitivity in all directions of space./ 3, 11 /

However, some interesting results have been obtained with the B V A design quartz crystal resonators. It is assumed that the quartz bridges support of the resonator in the B V A design allow reduction of most of the stresses, applied on the vibrating area involved in g sensitivity.

The goal of this study was to achieve a g sensitivity better than

3.10^{-10}/g with a HQ SC cut resonator encapsulated in HC 40 can (to be easily used in classical oscillators) in order to reach a good compromise between performances (ageing, g sensitivity, retrace), volume, warm up time and price.

This paper describes the design of such a resonator and the reproducibility of g sensitivity results from batch to batch.

The g sensitivity measurements are performed with a phase modulated reflectometer locked on the crystal mounted in a separated oven allowing a " 2 g tip over " test. Two differents phase modulation systems are described at 5 MHz and 10 MHz. (Fig. 7 - Fig. 8)

The 2 g test results are confirmed by 2 g test on oscillators and also by induced FM side bands under vibrations.

. I) THE PASSIVE REFERENCE SYSTEM

The principle of this system was presented by S.R. Stein in 1978 (ref.9) (Fig. 1). It consists in locking an oscillator of medium stability on a Xtal resonator driven in reflection. The output signal of the oscillator is phase modulated at an fm frequency. The output of this phase modulator is applied on the Xtal resonator with the help of a structural coupler. The reflected signal is amplified then detected. The oscillator is locked by using a synchronous detector working at the fm frequency.

In this system the most important part is the phase modulator which must be realized with care : this phase modulator must not exhibit amplitude modulation at its output. As a matter of fact the phase modulated signal after reflection on the Xtal resonator gives an amplitude modulated signal which presents a modulation index proportional to the frequency shift between the frequency of the oscillator and the resonance frequency of the Xtal. In this case all amplitude modulations at the phase modulator output have the same effects as frequency shift of the Xtal.

PHASE MODULATORS

Two types of phase modulators have been used in the present work. The first one is a digital modulator which exhibits a phase modulation index proportional to the frequency to be modulated : consequently this system is limited when the modulation index becomes too large, but since this modulator is a digital one, an exactly signal $\pi/2$ out of phase with respect to the modulating signal can be obtained. This signal is used as reference signal in the synchroneous detector.

The second one is an hybrid modulator (analog and digital), its upper working frequency depends only on the elements which are used to construct it. It needs a traditional phase shifter to obtain a quadrature signal for the reference channel of the synchronous detector.

- 1) Digital phase modulator

The phase modulation is obtained by using the time delay existing between the input/ouput signals of logic gates. A time delay ΔT produces a phase shift $\Delta\phi$ corresponding to

$$\Delta\phi = 2\pi \frac{\Delta T}{T}$$ where T is the HF signal period

By associating N gates in series, a phase shift can be obtained in the range 0 to $N\Delta\phi$ with $\Delta\phi$ steps.

A four bits multiplexer (Fig. 2) gives the possibility by using eight gates and one 4193 divider to obtain a triangular phase modulation by connecting together the 1-15, 2-14, 3-13, 4-12 multiplexer input pins. The resulting phase modulation is given on Fig.3. This modulator works correctly below 7 MHz with an amplitude modulation rejection of about 80 dB.

- 2) Analog and digital phase modulator

This system (Fig. 4) provides the addition of the modulating signal and the high frequency signal and the application of the resulting signal to a Schmitt trigger. The output pulse of the Smhmitt trigger is phase modulated with pulse width modulation. A monostable circuit sets this pulse to a constant value determinated by the time constant of the monostable. A sinusoïdal modulated phase signal is obtained with this system.

. II) MOUNTING CONFIGURATIONS

Numerous studies have been devoted to force frequency effect and acceleration sensitivity of quartz resonators

To prevent frequency variations due to initial static stresses applied on a resonator by the mounting supports, it has been shown that it does exist angles ψ for which the force-frequency coefficient / 6 /

$$k f (\psi) = \frac{\Delta f}{fo} \frac{2hD}{F} \frac{1}{N}$$

becomes equal to zero.

These points are given as ψ = 60° and 120° for an AT cut and ψ = 86 and 179° for an SC cut. Anisotropy was shown to have little effect on the force frequency effect.

In-plane acceleration sensitivity has also been studied.

These phenomenon allow to expect, for a four points mounting (XX', ZZ') configuration, a small variation of frequency for the AT cut. It must be pointed out that the locations of the mounting supports of an AT cut resonator, which minimizes the acceleration effects on the frequency, are not the same as those giving a null diametral force frequency effect.

Up to now, a study of acceleration sensitivity for the SC cut has not yet been published.

To solve the g sensitivity problem of a crystal resonator, we must consider all the forces (static and dynamic) applied on the vibrating area for all possible directions of acceleration in the full space.

Then we have considered all forces (surface and body forces, dynamic forces, initial stresses ...) which can be due to the mounting support or induced by an acceleration vector applied in a given direction.

Force frequency effect and in plane acceleration sensitivity must be both taken into account for the location of mounting supports, even if they do not give a full explanation of g sensitivity.

A more adequate model has been proposed to explain g sensitivity / 10 / (Fig. 5), involving the blank resonator and the mounting support taken in all directions. In this model, various forces are taken into account :

- surface and body forces
- torques comming from geometrical variation of the mounting ribbon
- induced compressive forces

With the geometry described in this reference (which assumes no initial diametral stresses), one can see that the distribution of volume forces is not equal to zero in the center of the plate, which is the area of interest.

On the other hand, all the static stresses Tj are equal to zero in the center of the crystal .

From the classical equilibrium relation :

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \mathrm{div}\ Tj + Fi$$

where u_i : are the displacement vector

Tj : strains

Fi : body forces,

we can see that any change in the distribution of body forces in the vibrating part of the crystal may induce a variation of resonant frequency.

A quartz resonator submitted to in plane acceleration ($\vec{\gamma}$) reaches the equilibrium from the balance between body forces ($m\vec{\gamma}$) and reaction forces due to mounting support, inducing a given stress distribution in the plate.

Submitted to out-of-plane acceleration (Γ_N) the resonator can be affected by diametral compression and torques. Furthermore, in this case, there is a lack of symetry in the plane of the resonator, which changes the diametral compression in static thickness shear stress in the vibrating part of the crystal, inducing a variation of frequency.

The mechanical equilibrium of quartz resonator submitted to any acceleration is modified in terms of the direction of this acceleration, inducing a change of the stress distribution in the plane which leads to a variation of frequency.

In summary, it comes from these studies that the in-plane sensitivity is now more or less completely explained and expected to be solved by an accurate positioning of mounting supports.

Geometrical symmetry of the whole device (including mounting ribbons) around x_1 x_2 plane of the resonator, seems to play an important role in the out-of-plane g sensitivity.

Roughly speaking, we have to solve nearly independently in and out of plane g sensitivities.

Among the studies dedicated to this problem, BVA design has offered an interesting solution to minimize g sensitivity.

The two main concepts of BVA design are non plated electrodes and quartz bridges as mounting supports. These bridges are supported by a quartz ring.

Ultrasonic machining is used to obtain these quartz bridges by removing quartz material.

The quartz bridge technique must reduce greatly the initial stresses due to supports. The mounting configuration can show a good symmetry in the main directions of the quartz plate. Shape, location and orientation of these quartz bridges can be easily chosen to minimize most of the effects involved in g sensitivity. Mounting supports can be located on the quartz ring, at any place regarding the location of quartz bridges or other parameters, such as Young modulus....

Furthermore this ring is a good mechanical filter, dissipating a part of the mechanical energy by its own deformation.

The whole structure (vibrating area, bridges,quartz ring, ribbons support) is expected to solve or to minimize the g sensitivity by reducing some initial and dynamic stresses.

. III) EXPERIMENTAL RESULTS

Following the conclusion described above, we have manufactured and tested various designs of QAS crystal resonators.

The parameters involved in this study were :

. number)
. location) of quartz bridges
. configuration)

To obtain the QAS design we have used the ultrasonic manufacturing. With this process, the positions of the quartz bridges can be accurately adjusted regarding to the orientation axis of the crystal. The positioning is given by a goniometric table.

In order to achieve a low g sensitivity, it has been shown that the effects of Γ_T and Γ_N must be solved independently.

To prevent g sensitivity coming from diametral compression (initial stresses, Γ_N), the location of bridges were choosen around the zero of the $K_g(\psi)$ curve applying to SC cut. (Fig. 6)

" In-plane " g sensitivity (Γ_T) is mostly due to stresses at the boundary between vibrating area and quartz bridges.

The flexibility of the mounting and of the bridges has an effect on Γ_N .

Location, various ratios of widths, lengths and thicknesses number of bridges between the vibrating area and the surrounding allow solutions to both sensitivities.

Among the various designs we have tried, the most significant are :

- 2 bridges (along ZZ' or XX')
- 4 bridges (XX' and ZZ' with dimensions eventually different on each axis)
- 4 bridges located at minimum of young modulus
- 4 bridges located at φ angles given by $k_j(\varphi) = 0$ (Fig. 6)
- 4 bridges symmetrical versus given direction

In this later configuration, it is expected that the superposition observed by Lukaszek and Ballato will apply, meaning that two diametral forces giving opposite effects will balance each other.

In each configuration of quartz bridges, we have tried various mounting support (2 or 3 points).

Two bridges and three points have allowed very low g sensitivity results but with a wide dispersion inside each batch of resonators, from $3.10^{-11}/g$ to $8.10^{-10}/g$

Insofar as our goal was to achieve $3.10^{-10}/g$, we have selected a configuration for which we obtain a good percentage of resonators below this limit.

In the first batch manufactured by using this design, the results in g sensitivity can be summarized by the following table :

$\leqslant 2.10^{-10}/g$	$\leqslant 3.10^{-10}/g$	$\leqslant 4.10^{-10}/g$	$\leqslant 5.10^{-10}/g$	$\leqslant 7.10^{-10}/g$
16 %	36 %	50 %	60 %	80 %

To test the reproducibility of the design and of the working procedure, we have manufactured three batches (50 pieces each) using the same structure.

The statistical results are given by figure 9 on which we can see, more or less, the same g sensitivity distribution.

We verify that 35% of resonators, in each batch, have a g sensitivity smaller than $3.10^{-10}/g$. These resonators being devoted to highly stable oscillators, g sensitivity with good electrical parameters, short term stability, retraceability ... are of great interest.

The Table II gives standard parameters and short term stability measured with the phase modulated reflectometer (Fig 10) or oscillator. Additional results reached by oscillators using such resonators can be founded in the paper given by C. BEAUVY

F (MHz)	L (H)	R (Ω)	Q (10^6)	$\sigma_y(\tau)$ (PMR) 10 s	100 s	Retrace 25°C 24 H
10 MHz or 10.130 MHz	1,2	63	1,2	1.10^{-12} 6.10^{-13}	1.10^{-12} 5.10^{-13}	2.10^{-10}

TABLE II

From table II, we see that these resonators could be successfully used in high quality oscillators.

These results show that the QAS design has allowed great improvement to some interesting features such as short term stability or retraceability.

These improvements are assumed to be mostly due to homogeneity of the mounting of the quartz on its base through the quartz bridges.

CONCLUSION

Our work leads to the definition of a new design of HQ 10 MHz SC cut resonators (QAS).

With this design, we obtain for all directions of space a low g sensitivity with a good reproducibility from batch to batch.

35 % resonators manufactured have g sensitivity better then $3.10^{-10}/g$. The best resonator was measured down to $3.10^{-11}/g$ on the worst axis.

We are still working on the design of quartz bridge in order to increase the ratio of low g sensitivity resonators by batch.

These resonators are shown to have very interesting factors to be used in high quality oscillators for military or space applications (low ageing rate, good retraceability, fast warm up) in addition to all advantages of classical SC cut (static and dynamic thermal behaviour, anisochronism ...).

It must be pointed out that the equipment we have described (PMR) allow sorting of the crystals during final production tests before the implantation in oscillators (g sensitivity, short term stability).

CEPE is using B.V.A. techniques due to R. J. Besson and his group (P. Maitre, J. P. Valentin and others...). Manufacturing is being developed with proper cooperation of the group.

(Patents No. 7601035 and No. 8315652-8315653-8315654)

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CEPE French patents N° 8315652 - 8315653 - 8315654

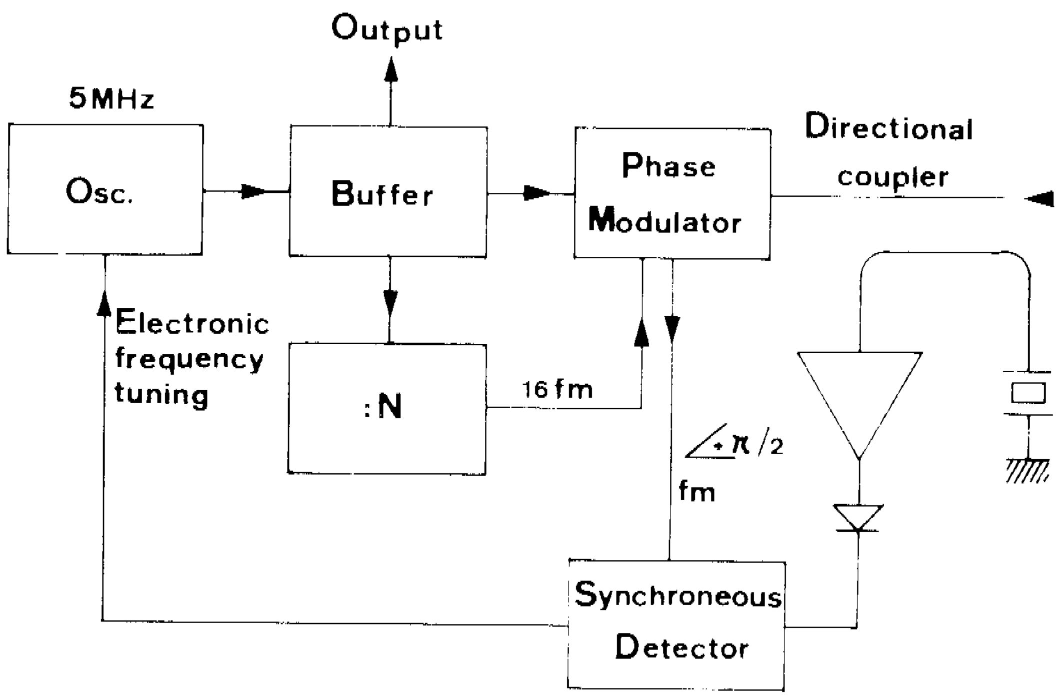
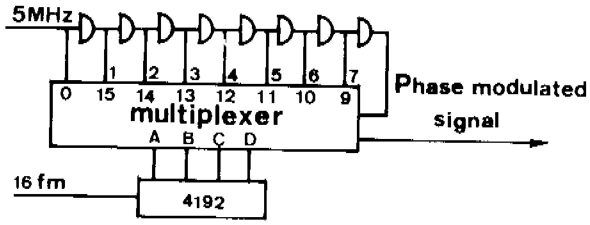
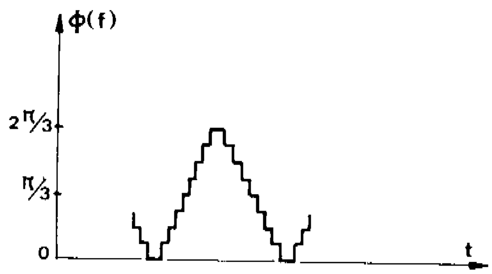


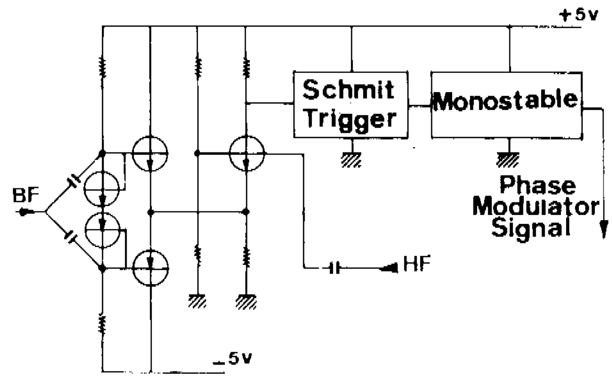
Fig 1 SCHEMATIC DIAGRAM OF THE PASSIVE REFERENCE SYSTEM



Digital phase modulator



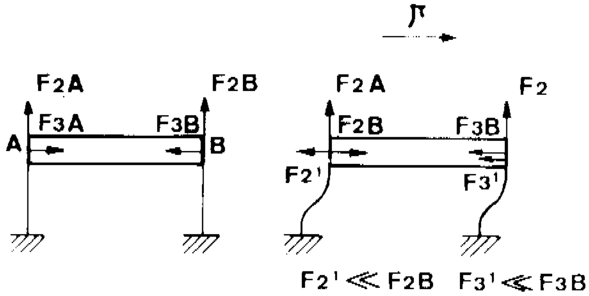
Resulting phase modulation obtained with the digital phase modulator



ANALOG AND DIGITAL PHASE MODULATOR

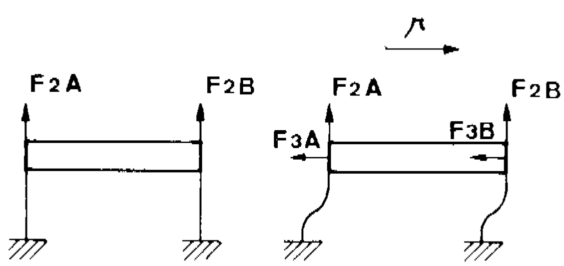
Fig. 2 Fig. 3

Fig. 4



static dynamic

STRESS MODEL



static dynamic

Fig5 ACCELERATION MODEL

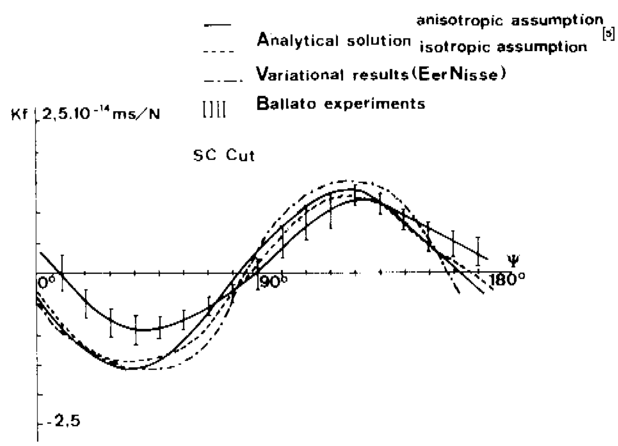


Fig. 6

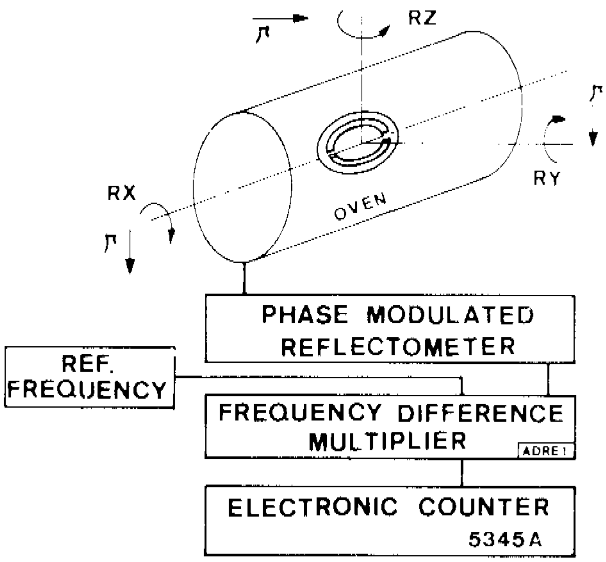
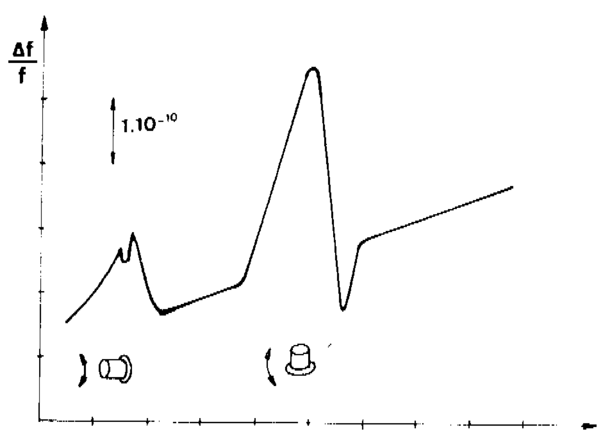


Fig 7 G. SENSITIVITY TEST BENCH

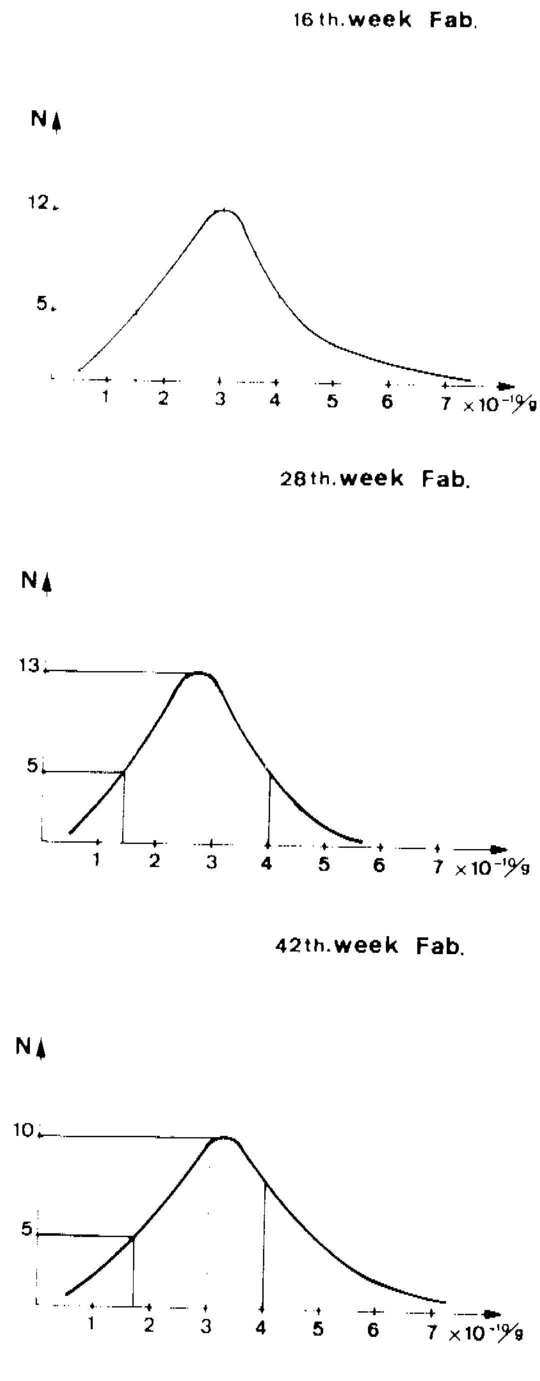
AND

SHORT TERM TEST BENCH



2 G TIP OVER TEST

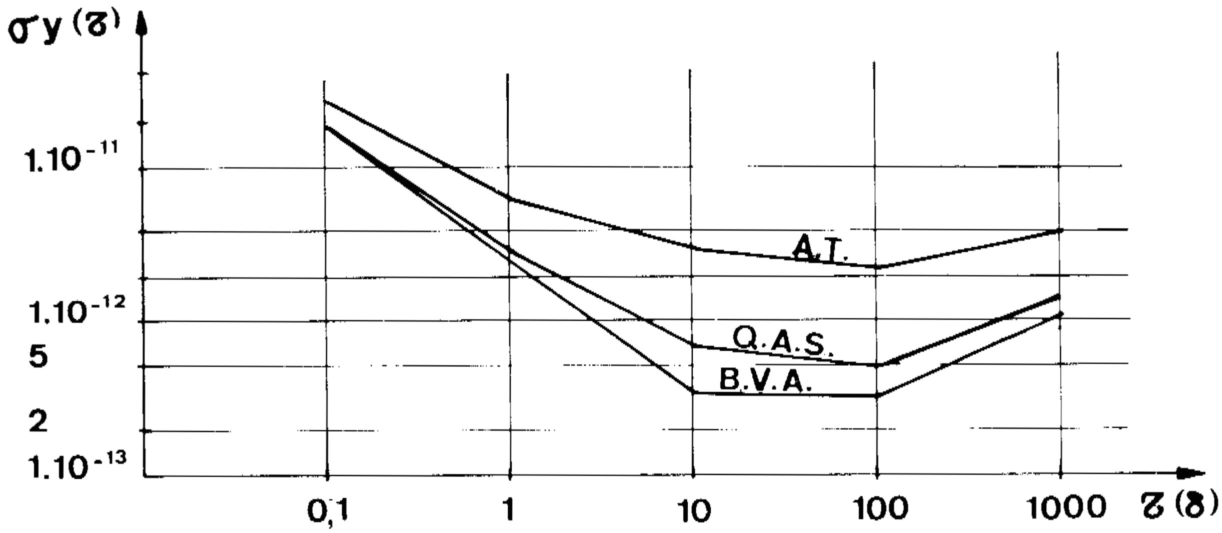
Fig. 8



g SENSITIVITY VALUES OF

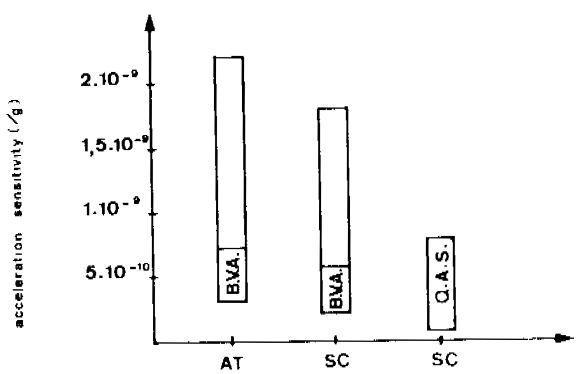
SEVERAL BATCHS

Fig. 9



SHORT TERM STABILITY

Fig. 10



ACCELERATION SENSITIVITY

Fig. 11

QUESTIONS AND ANSWERS

MR. VIG:

Mr. Vig, U.S. Army. The blank size of your resonators is significantly larger than the conventional resonator. Have you ever made any resonators without the bridges to see what a large diameter resonator without the bridges would do, compared to the one with the bridges? What I'm really asking, is the improved performance definitely due to the bridges or could it be due to the fact that you are using a much larger diameter blank?

MR. DEBAISIEUX:

The ten mehagertz resonators, the dimension of the blanks is 15mm and the dimension of the ring is variable. For example, we have two designs where the dimension of the ring is different. The dimension of the ring is very important for the sensitivity to accelleration. And the dimensions of the quartz bridge is also very important.

MR. CLARK:

I have one question. Do you think it's the dimensions of the quartz bridge that accounts for the range of a factor of ten in g sensitivity, of three parts in ten to the eleventh? It's mainly the dimension of the quarts bridge that accounts for that?

MR. DEBAISIEUX:

Yes. At the present time we have resonators with g sensitivity as low as 5 parts in 10^{-11} per g. Mr. Vig, I see an oscillator in your laboratory where the g sensitivity of resonator is five times 10^{-11}/g.

MR. WALLS:

Fred Walls, N.B.S. Have you had a chance to look at the differences with different quartz for the blank; swept quartz, natural quartz, etc. on the sensitivity? Does the g sensitivity or your resonators depend upon the quartz from which it is made? Have you looked at the differences in performance for natural quartz, synthetic quartz, swept quartz?

MR. DEBAISIEUX:

No. At the present time we use two quartz: Sawyer and (Essisan's) quartz and we cannot see the difference of the g sensitivity of quartz, caused by quartz.

MR. WALLS:

Do you have some speculation as to why the wide variance of the three-ten-eleven range, and yet many of them are still above $2x10^{-10}$? Why the wide dispersion in g sensitivity?

DR. McCOUBREY:

He is asking, I think, why differences in g sensitivity from the one batch of crystals to the other? I think you already mentioned that the dimensions of the quartz bridge connecting the oscillator plate to the framework makes a difference, but perhaps you can comment on reasons for the difference.

MR. WALLS:

The dimensions of the quartz bridge are very carefully controlled in thickness and so forth, so I don't understand why that would explain the wide dispersion. Do you have some idea as to why there is such a difference in one batch between one resonator and another on g sensivity?

MR. DEBAISIEUX:

The dimension and location of the bridges are important. The dimensions are more important than the location but it's not necessary to look at the quartz bridge with high precision.