THE APPLICATION OF HARDENED CRYSTAL REFERENCE OSCILLATORS INTO THE HARDENED SUBMINIATURE TELEMETRY AND SENSOR SYSTEM (HSTSS) PROGRAM

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ABSTRACT

This paper briefly reports on concepts for hardening (physically toughening) crystal reference oscillators for the highly integrated program known as HSTSS. Within the HSTSS program is the L & S band transmitter development contract. The harshest requirements for this contract are surviving and functioning, to within 20 ppm of its center frequency, 30 ms after sustaining a shock pulse of 100,000 (g) for 0.5 ms on any axis. Additional requirements call for the transmitter to be no larger than 0.2 in^3, and to operate within a 20 ppm frequency stability throughout the temperature range of -40^0 to $+85^0$ centigrade and during centrifugal spins of up to 300 Hz or 25,000 (g). Fundamentally the question is, is it feasible for any telemetry system to be capable of withstanding such harsh conditions and, to be practical on all DoD Test Ranges, still adhere to the stability tolerance guidelines set forth by the Range Commanders Council on Telemetry Standards - IRIG 106-96? Under "normal" conditions, stability requirements for "Range" transmitters are easily satisfied through the use of off-the-shelf crystal reference oscillators which provide the reference frequencies required within a transmitter's phase lock loop circuitry. Unfortunately, the oscillator is also the most vulnerable part of a transmitter to the conditions listed and is the key to this problem. The oscillator's weak points are in its resonator's fragile quartz structure (the blank) and support mechanism. The challenge is to invent and adapt this area to these newer harsher conditions and to do it in the smallest space ever required.

KEY WORDS

Hardened Telemetry, High-g Instrumentation, Crystal Reference Resonators and Oscillators

INTRODUCTION

The overriding issue for any DoD telemetry system is its adherence to the regulatory guidelines set forth by IRIG 106-96. The issue centers on frequency management. Staying within ones assigned frequency while conducting Range operations. From a technical point of view, this issue ties back to the stability of the transmitter and to the reference oscillator which controls that stability. Frequency instabilities are generally caused by environmental conditions, barring any overt design or component problems. Traditionally, highly stable transmitters have used crystal reference oscillators, since under "normal" conditions, they provide the highest stability of any known substance due to their own natural piezoelectric properties. However, as a whole the crystal industry has not had much involvement with "high-g" or miniaturization. In part, this is due to a lack of market place interest or requirements, and is tied to the paradigm in thinking that high shock and crystals are completely incompatible. Consequently, the whole crystal industry is non-standardized in this field with many approaches conflicting in theory. To date most work has been trail and error, and because of the proprietary nature of the game, mistakes and successes are not know or universally understood. Technically, very few choices are even available. The crystal reference oscillator is thought to be best suited for this application because of the already existing work at higher (g) and the development in them, over the last 20 years, to specifically address frequency management and stability issues. In May of 1999, the US Army Yuma Proving Ground in Arizona awarded a contract to develop oscillators to meet the above harsh requirements. This contract is of particular importance since both the HSTSS Transmitter and Data Acquisition contracts are looking to it for success as a reference oscillator and as a clock, respectively.

BACKGROUND TECHNICAL INFORMATION

ABOUT QUARTZ

Quartz naturally exhibits piezoelectric properties. Applying a voltage to the opposing surfaces of a piece of properly oriented quartz (the Blank) will make it change shape or deform mechanically. Conversely, mechanically deformation of the quartz blank will produce a corresponding voltage. The natural mechanically resonance frequency of the crystal blank can be exploited to produce an AC frequency signal by applying a similar AC voltage frequency through a feedback loop amplifying circuit. Start up is automatic from the DC powered amplifier, which with the proper feedback will sustains the oscillation at that natural frequency. The frequency is determined by the cut, size and thickness of the blank. Although there are many crystal cuts, the most commonly used at higher frequencies (one MHz and above) is the AT cut. The AT cut is the first discovered temperature compensating cut and depends strongly on the angle and precise direction of the cut with respect to the crystallographic axes of the quartz bar.
See Figure 1.

RESONATORS
A resonator is a structure that hermetically houses the crystal blank, the blank's support mechanism and its electrode connections. In an AT resonator, the blank is an AT-cut piece of quartz with two parallel or slightly convex surfaces, usually about the size of a nickel or less. Electrical connections are made to the crystal by metallizing the two parallel faces on opposite sides of the crystal blank. These electrical connections also act as the support post, which suspends the blank inside the housing structure. The crystal's resonant frequency is inversely proportional to its thickness between these two metallized surfaces. Applying a voltage between the two metallized surfaces causes the AT crystal to move sideways internally in a thickness shear movement, as shown in Figure 2.

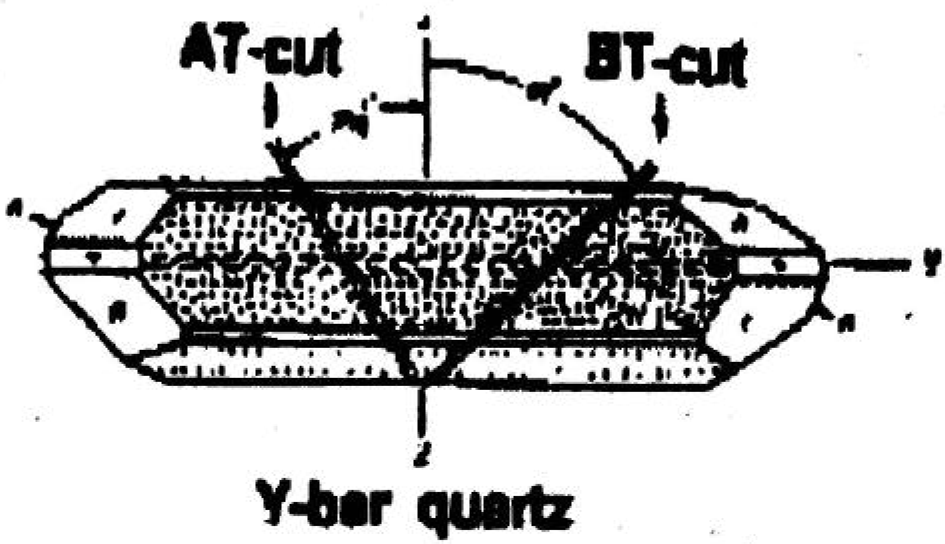

FIG. 1 Orientation of the AT-cut to the quartz bar.

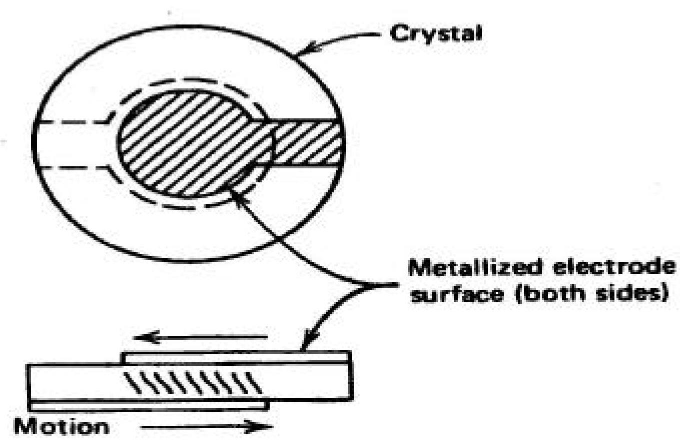

FIG. 2 Shear motion of an AT-cut crystal at fundamental resonance.

CIRCUIT

A traditional equivalent circuit using lumped constant elements for the crystal is shown in Figure 3. The R_S, L_X, C_X portion of the circuit represents the "motional arm," which arises from the mechanical vibrations of the crystal itself. Inductance L_x and series capacitance C_X represents the crystal's frequency-sensitive elements. C_0 is called the shunt capacitance, which is the capacitance between the two-metallized surfaces. This also includes the electrode contacts attached to these surfaces. This capacitance usually runs about 3-15 pF for most crystals. The series resistance R_S of a typical crystal of any type of cut varies from about 10 ohms at 20 MHz to a few hundred ohms at 1 MHz. C_L is a load capacitor and is shown in series. This capacitance is often used to tune the resonator. By making C_L a varactor and coupling it with a thermister, external temperature compensation is possible. The idea is to pull the frequency to the opposite direction of the temperature effect by using a temperature sensing thermister, which responds by sending a corresponding voltage to the varactor C_L. The varactor responds by automatically adjusting its capacitance to the new voltage received.

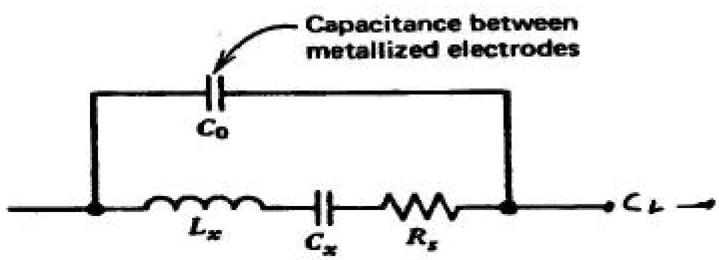

FIG. 3 Equivalent circuit for a quartz crystal near fundamental resonance.

GENERAL

Given enough space and power, many extreme conditions such as high or low temperatures or shock can be nullified through physical buffering or isolation. Successful techniques for nullifying temperature effects have been through oven controlling, varying the angle on how a crystal blank is cut from its quartz bar and pulling the frequency of a resonator in the opposite direction from its temperature effect by changing its capacitance. For shock, most of the technology today is crude and centers on techniques of padding or suspensioning. In the past 10 years, some advancement has been made with the concept of using a flat quartz sandwich type structure for protecting the crystal blank from shock and to insure that the blanks used were free of physical scratches. Traditional, methods for mounting blanks usually consist of two, three and four point mounting designs, where small springy wires are bonded to the metallized surfaces of the blank. Support designs range from tabletop to paddle type structures. See Figure 4. Drawbacks on many of these approaches are still increases in overall size, power consumption, warm-up time and cost, as environmental conditions generally worsen.

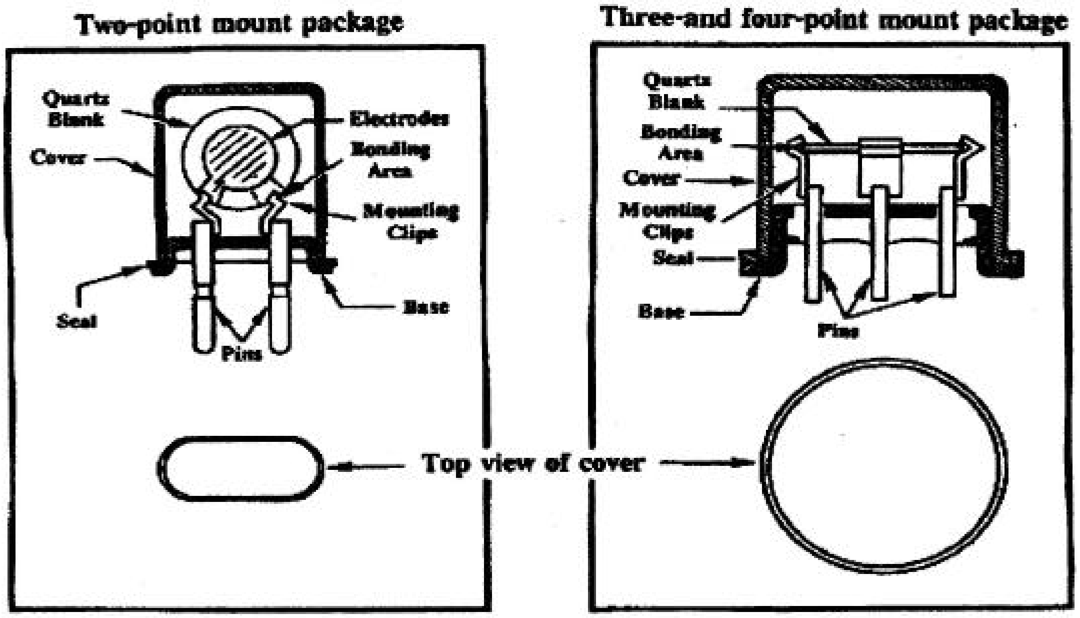

FIG. 4 Typical construction of AT-cut and SC-cut crystals.

CONCEPTS FOR HARDENING AND MEETING REQUIREMENTS

PROBLEM

Technically, the apparent dilemma HSTSS faces is in its requirement of being subminiature, therefore, not having the luxury for the physical space traditionally required for solving the "normal" environmental requirements, let along the extreme ones. Specifically, the extreme environmental requirements that must be addressed are: Surviving high-g shocks of 100,000 (g) for .5 ms on any axis; Operating within a 20 ppm stability during centrifugal spins of up to 25,000 g; Operating within a 20 ppm stability through the temperature range of -40^0 to $+85^0$ centigrade; and To have an oscillator no bigger than 0.35" X 0.3" X 0.15" or a volume of less than 0.058 in^3.

HIGH (G) BLANK

Recently, a new theory has emerged where "hardening", protection against high (g) in this case, does not necessarily mean big, thick or even padded, but relies on the concepts of smallness and the elimination of flaws and stresses within the crystal blank's structure. The concept of smallness simply means less mass, therefore, less (g) effect! Techniques for cutting down the physical size of the crystal blank are the key here, since the frequency of a crystal is inherently tied to its size or mass. The larger the crystal the lower its frequency and conversely, the smaller a crystal the higher its frequency. The concept of reducing flaws and stresses to increase how much force or shock a crystal structure can physically take before failure, not only makes sense, but is well founded in the science of crystal theory. Flaws and stresses are points of initiation for fractures that lead to breakage. Flaws to a crystal blank are scratches, nicks or can be external contaminates, such as imbedded polishing compounds left in from processing. On a molecular basis, flaws can be within the crystal lattice where the silicon dioxide quartz structure has not correctly formed or metallic trace ions (Na, Al, and Fe) are substituted or trapped within the crystal matrix. Stress is stored energy in the form of non-uniformed and undistributed bond energies. Abrupt relief of that energy can result in fractures within the crystal matrix.

The point or theory is: Given a perfectly flawed and stressed free crystal blank; there is a point where a sufficient reduction in mass will yield an inherent frequency and a structural integrity capable of surviving a corresponding maximum force.

For the HSTSS program, that maximum force is 100,000 (g), at a frequency of 20 MHz with its crystal mass significantly reduced and free of flaws and stresses. The thought is, through processing and good standard methods and practices, the flaws and stresses can be eliminated. Note: During the manufacturing process, high purity materials, high standards, carefully controlled curing and annealing techniques, and an environment free of contaminants are mandatory for producing the kind of results and reliability required.

SWEEPING

Sweeping, is a process which removes excess ions, mainly sodium ions, during the quartz growth process. The process consists of introducing the quartz ingot to heat and a strong electric field. Excess ions migrate to their prospective ingot ends. Those ends are cut away, leaving a "swept" quartz ingot. The technique was first used to harden against radiation, which the Sodium ions absorb causing frequency instabilities. According to theory and some evidence, it is thought that this technique will also further harden crystals against shook.

HIGH (G) MOUNTING

The other part of this problem involves the actual mounting of the crystal blank itself or its support mechanism. It is the combination of the blank, the mounting of the blank or supports of the blank, the electrode connections and the hermetically containing of the blank which all makes up the resonator. The **state-of-the-art concept** and goal is to mount a rectangular shaped quartz blank as a cantilever between two ceramic lids. One end of the cantilever is fixed while the other end is dampened with supporting material to further guard against extreme shock. This design is thought far superior to traditional mounting methods and has already been proven successful to shocks of 30,000 (g). The goal is to further miniaturize this process from the current existing design.

HIGH (G) OSCILLATOR

Techniques for hardening oscillators rely on smallness and short direct connections. Modern high-density plastics packaging, when properly potted, have shown capable of surviving in excess of 100,000 g. On a circuit level, pierce designs have shown good stability under harsh conditions. It is though that the combination of an integrated simple pierce design to the hardened resonator, using the same techniques discussed above, should meet the intended goals.

TEMPERATURE

It is thought that the HSTSS temperature stability requirement can be met with the proper AT crystal cut only. No external temperature compensation would be necessary. See fig. 5. Note: This is also in line with the theory of smallness for surviving high-g and is absolutely necessary if the oscillator is actually expected to meet the restrictive space requirement.

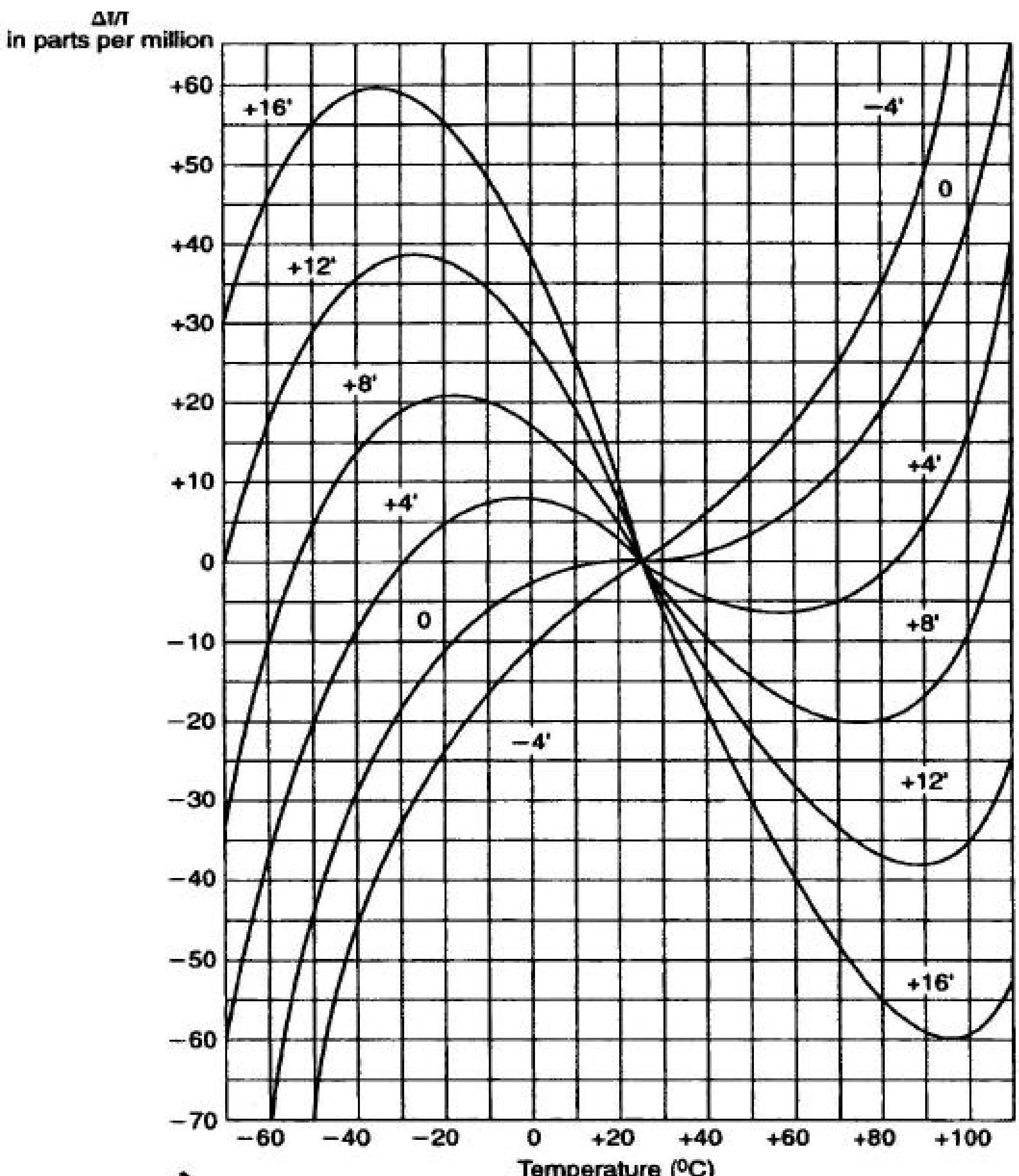

FIG. 5 Temperature characteristics of AT-cut crystals versus slight changes in cut-angle.

STABILITY UNDER HIGH (G)
How does high-g influence the stability of an oscillator during its operation? Given that the resonator does not fail or the blank is not pinned against a surface, best estimates are that a frequency gives rise to change by 10^{-9}/g to 10^{-10}/g. At 25,000 (g) the change in frequency `f_o would be between 2.5 to 25 ppm. Note: The Transmitter requirement is 20 ppm and the Data Acquisition requirement is 200 ppm.

CONCLUSION

The HSTSS strategy of theorizing about high-g oscillator successes and conducting a thorough search for companies practicing those same theories, has successfully lead to the contractual award of a development contract with STATEK corporation, the leading manufacturer in the field of high-g oscillator work. Base on this company's previous work, current developed products and theories of practice, it is concluded that the stability goals of the HSTSS Transmitter program are feasible. Crystal reference oscillators meeting the discussed desired goals will be available at the end of FY 2000. Other oscillators, a 500 (g) and a 30,000 (g), meeting similar goals will be ready early and mid FY 2000, respectively.

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