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INVESTIGATION OF FAST REACTION SAW ACCELEROMETER

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4.0 FUTURE PLANS

During the next year, investigation of several major tasks will be considered. These tasks are:

Task 1 - Design and fabrication of a new 350 MHz SAW resonator based on a powerful theoretical simulation program that we are currently initiating.

Task 2 - Using the above resonator, a long-term stable SAW oscillator will be constructed with a computer automated test-bed system for long-term aging data collection.

Task 3 - Cantilever beam design and fabrication of accelerometer using the SAW oscillator resulting from Task 1 and Task 2.

Task 4 - Hermetic sealing and packaging of the accelerometer sensor.

Task 5 - Dynamic test of this SAW accelerometer under variable frequency and variable input accelerations.

5.0 REFERENCES

1. A.P. Andrews and M.E. Motamedi, "Monolithic Accelerometer," Final Report, Contract No. DASG60-79-C-0021, September 1983.

2. W.E. Rosvold and M.L. Stephens, "Cantilever Accelerometer," AFAL-TR-77-152, WPAFB, OH, 1977.

3. M.E. Motamedi, "Passivation on High-Q Acoustic Strain Sensors for Accelerometer," Final Technical Report, Contract No. F49620-82-C-0012, November 1984.

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The objective is to develop SAW accelerometers with improved bias stability characteristics for moderately accurate inertial navigation. Methods of fabricating dual-resonator crystals with low absolute and differential aging characteristics have been developed. Tests have been performed at 10 Gs acceleration on integrated noise levels for simulated guidance system mission times of up to 20 min. Error rates less than 15 meters per hour in position of accuracy and velocity error less than 0.013 m/s have been achieved. Sensor device has a frequency stability of part in 10^{10} with a dynamic range of 10^6. Simulation shows a bit quantization of 1.3×10^{-3} m/s and frequency scale factor of 770 Hz/m/s^2 can be achieved.

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1.0 INTRODUCTION

Inertial sensors are used for navigation guidance and flight control in airborne weapon systems such as cruise and MX missiles. The cruise missiles use the force-rebalance accelerometer in which the current waveforms for electromagnetic forcing of the proof mass are digitized as pulses. Such accelerometers require precision electronics, machining and assembly; hence, the cost is high. In addition, the warm-up time for stabilization is long (typically in minutes).

Therefore, a need for more reliable inertial sensors is constant. Many technological approaches have been reported for meeting this need. Those which have received much attention are: solid state accelerometer[1], piezoresistive[2] and SAW accelerometer.[3] All of these approaches use a "proof mass" which is connected to the host vehicle by means of a stress sensor. The stress sensor measures the force applied to the proof mass, which is proportional to the sensed acceleration of the host vehicle. These are "open-loop" sensors, because the force is not applied by a precision servo loop, as in the case of the gyroscopic and pendulous accelerometers.

Planar cantilever devices or solid state acclerometers sh promise for meeting these needs with an open-loop accelerometer without bearings or points of wear. By using established planar fabrication techniques, an integrated circuit containing strain-sensitive elements on a substrate which acts as a clamped plate or beam can be made. Acceleration forces on this device will cause surface strains that are sensed and processed by the electronic circuit. This type of accelerometer has the potential of being inexpensive because it uses little power and can be made small and reliable.

In this work we are reporting the cantilever beam SAW accelerometer as a new approach for solving many existing problems dealing with the conventional accelerometers. An existing problem is the large temperature range requirement. Conventional accelerometers are not likely to perform as well as cantilever devices over large temperature variations, because their design depends on different properties of different materials, which are difficult to maintain in the proper relationship over large temperature variations. For example, floated devices depend on fluid buoyancy and viscosity, and most likely they cannot be adequately matched over a large range of temperatures. Similarly, electromagnetic and drag-cup device designs depend on the mechanical and magnetic properties of magnetic and nonmagnetic materials, and most likely these properties cannot be adequately matched over large temperature ranges. Also, the thermal expansion of dissimilar materials causes stresses or strains that lead to mechanical instability in clamped assemblies with repeated temperature cycling.

Surface acoustic wave (SAW) technology offers an approach for an inherently digital acceleration sensor with no precision electronics and machining assembly. This technology uses established planar photolithograph for low-cost fabrication. The associated electronics contains only one active element (transistor). Simplicity makes this an attractive candidate for digital sensor applications in future missiles and manned and unmanned aircraft.

The SAW resonator is a strain-to-frequency converter. It consists of an interdigital transducer between reflective gratings on a piezoelectric (quartz) substrate. A signal applied to the transducer launches Rayleigh-mode waves along the surface of the substrate, which are coherently reflected by the gratings. A feedback electronic circuit maintains the cavity in resonance. This uses a single dc voltage source for power, and generates an output signal at the resonator frequency. An additional buffer amplifier may be required for signal level shifting to compatible logic levels.

Longitudinal strain applied to the resonator cavity will cause a proportional change in its resonant frequency. This provides a bit rate frequency output proportional to strain input. This relationship forms the basis of the simplest SAW accelerometer, which is a simple cantilever-beam configuration. Acceleration applied at the clamped end is transmitted to the proof mass at the free end through bending stress. The resulting surface strain along the SAW resonator causes a frequency shift which is proportional to the applied acceleration.

2.0 OBJECTIVE

The objective of this program is to perform fundamental studies on SAW sensors using quartz substrate with improved bias stability characteristics. Methods of fabricating dual-resonated SAW sensors with low differential aging have been developed. Dual-resonator crystal combined with hybrid oscillator circuitry has shown excellent stability on the order of 1×10^{-10}. Solid state sensor of this kind performs a position error smaller than 5 m for a mission time of 18 min. A complementary technique based on silicon monolithic technology can also be used for developing inertial sensors. Devices of this kind demonstrate advantages such as small size, low cost, and ease of signal processing.

Our investigations indicate that solid state inertial sensor is a breakthrough solution to modern strategic applications.

3.0 RESULTS

3.1 SAW Accelerometer

Accelerometers are needed for guidance, stability augmentation, and navigation of guided missiles and aircraft. For applications in future tactical systems, these accelerometers should be less expensive, more reliable, and smaller than the floated gyroscopic accelerometers, drag-cup velocity meters or electromagnetic force-rebalance accelerometers now in use. For missiles and other applications where rapid reaction is a necessity, these devices must be able to operate without first being thermally stabilized at a given operating temperature.

The program plan is to perform studies on SAW temperature compensation methods that yield improved stability characteristics required of inertial navigation accelerometers. Also included in this program will be evaluation of the transient thermal response of the SAW resonator cavity and amplifier electronics and of the feasibility of meeting the requirements as given in the tasks.

During the first phase of this effort, methods of fabricating dual-resonator crystals with low absolute and differential aging characteristics have been developed. Also hybrid oscillator circuitry has been studied, and preliminary results using dual resonators sensing crystals show excellent stability, typically less than 1×10^{-10} for 1 s average times. Tests have also been performed on integrated noise levels for simulated guidance system mission times of up to 20 min. Error rates less than 15 m/h in positional accuracy have been achieved. These data indicate that SAW accelerometers are considerably better than existing moderately accurate sensors which commonly have an error rate of 1 n.mi (equivalent to 1852 m) per hour.

Planar cantilever devices show promise for meeting these needs with an open-loop accelerometer without bearings or points of wear. Making an integrated circuit containing strain-sensitive elements on a substrate which acts as a clamped plate or beam is possible using established planar fabrication techniques. Acceleration forces on this device will cause surface strains that are sensed and processed by the electronic circuit. This type of accelerometer can potentially be inexpensive. It uses little power and can be made small and reliable.

3.2 SAW Resonator

The Surface Acoustic Wave (SAW) resonator can be fabricated on the surface of the piezoelectric substrate, like quartz, using a planar process technology. This device can be used as a feedback element for precise high frequency oscillator. A SAW resonator consists of two reflectors and one or two interdigital transducers which together form a resonance cavity.

For the past ten years, surface acoustic wave oscillators have been competing as alternative IF frequency sources to bulk wave crystal oscillators. They are currently used in numerous military and satellite applications, resulting in a power savings of 100:1, and a size reduction of 20:1 over bulk oscillators. SAW oscillators operate at fundamental frequencies beyond 1 GHz and have properties which effectively improve phase noise performance to the elimination of frequency multipliers and phase-lock loop circuitry.

In controlling device characteristics such as temperature compensated frequency stability, high-Q, and low-phase noise, choice of substrate materials is an important decision in the design. To date, single crystal quartz is used with several different crystal orientations applied. The lowest temperature coefficients have been achieved with the ST cut quartz. Since SAW resonators are presently fabricated on piezoelectric substrates, hybrid circuit technology must be used to construct a SAW oscillator.

The surface acoustic wave resonator is a planar electrode structure photolithographically defined on a suitable piezoelectric material. The SAW resonator functions in much the same manner as a conventional quartz oscillator crystal.

Acoustic waves are generated by an interdigital transducer which provides electrical-to-mechanical, as well as mechanical-to-electrical signal transduction. The acoustic waves are confined within a cavity whose boundaries are accurately maintained. The Q of the cavity is determined by the material losses and cavity leakage. The same excellent frequency controlled properties of bulk wave quartz resonators is achieved by SAW resonators provided that the fabrication techniques are closely controlled. Figure 1 is a schematic representation of three common types of resonator designs. The simplest type is that in Fig. 1(A), which is a single-pole, single-port resonator structure.

The one-pole, one-port resonator of Fig. 1(A) has inherently low cross talk and lower insertion loss. The structure shown in Figs. 1(B) and 1(C) have higher insertion loss due to propagation losses of an acoustic signal in the center of the cavity. However, these types of resonators have the advantage of a 180° phase shift required for construction of a positive feedback resonator controlled oscillator.

On either side of the input/output transducer are two gratings which contain a large number of reflecting structures with a periodicity slightly less than that in the transducer. The gratings act as mirrors when the acoustic wavelength is approximately equal to twice the grating periodicity. In this frequency range, all surface acoustic wave energy is confined within the cavity formed by the two gratings. Each grating acts like a mismatched impedance in the transmission line, causing a reflection. With a sufficient number of gratings, a total reflection from all the gratings can be achieved very nearly equal to the incident wave from the IDT transducer. At the resonance frequency, all of the reflections add in phase, resulting in a narrow band signal with extremely high Q factor.

Although the single-pole resonator has many desirable properties, it does not have the design flexibility of the two-pole device. When inserted in an oscillator circuit, the single-pole resonator must be phase-shifted almost 180° in order to feed back an in-phase signal into the input of the amplifying

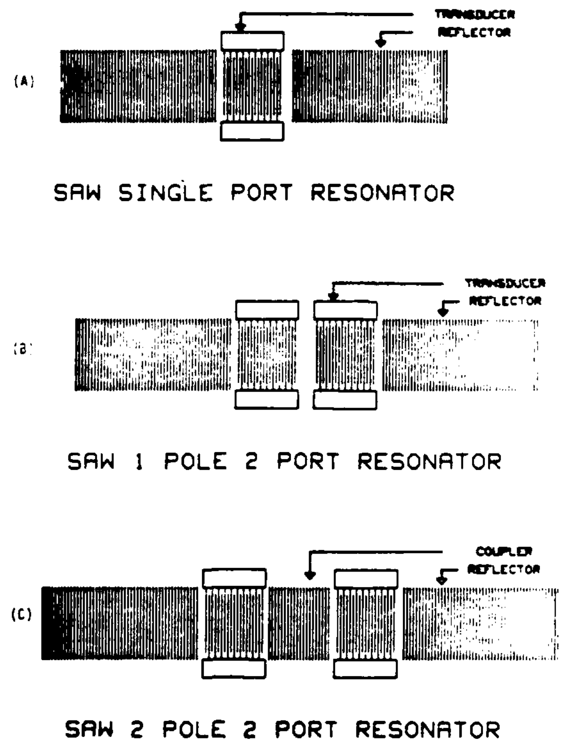

Fig. 1 SAW resonator cavity structures.

active device in the oscillator. The two-pole device, on the other hand, allows for the 180° phase shift simply by reversing the connection leads in the second IDT structure, thus reversing the phase. Achieving the 180° required phase shift in the single-pole resonator may in fact increase the phase noise beyond what can be achieved by a conventional two-pole resonator.

3.3 Temperature Compensation Technique

Methods of temperature compensating SAW oscillator-sensors were investigated. Design studies indicated temperature compensation circuitry, configured as shown in Fig. 2, could maintain the sensor frequencies provided a phase shift opposite to that of the surface wave crystal could be introduced, in this case a parabolic temperature characteristic. Several circuits were designed using varactor diode phase shifting networks.

To test the design feasibility, experimental temperature compensated oscillators were built. Surface wave two-pole crystal filters were used as feedback elements to extend the temperature range over which the oscillators could be compensated. Prototype crystals operating nominally at 198 MHz were fabricated and placed in oscillator feedback circuits which contained parabolic phase shifting networks.

Frequency vs temperature for a test circuit over the range 0°C to 100°C is shown in Fig. 3. Multiple scans are shown indicating hysteresis which was due to unsealed crystal units in these prototype circuits. Nevertheless, temperature compensation is evident; and the frequencies were held to within ± 35 ppm, as shown by the dashed limits. A sharp drop in frequency with increasing temperature at 45°-50°C was due to a higher-order resonator transverse mode in the SAW two-pole crystal phase slope. Improvements in the crystal design to eliminate transverse modes and proper sealing of the crystals to eliminate hysteresis are expected to result in compensation of ± 10 ppm over the temperature range -30°C to 100°C.

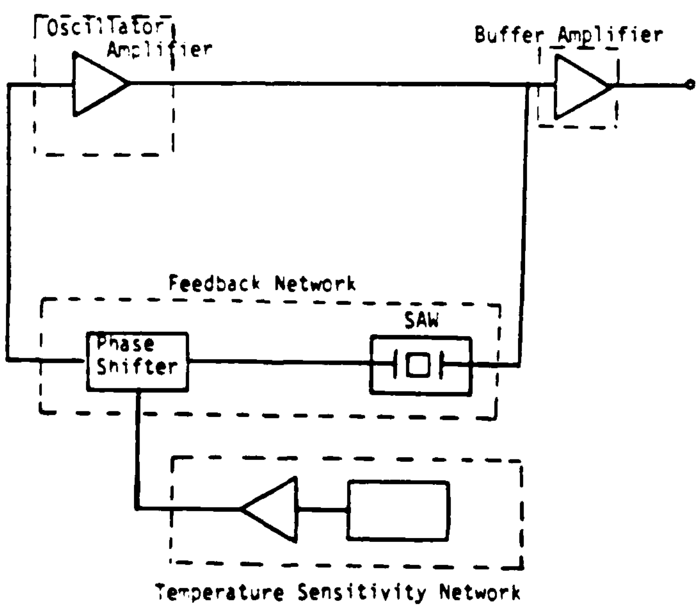

Fig. 2 Temperature compensated SAW resonator.

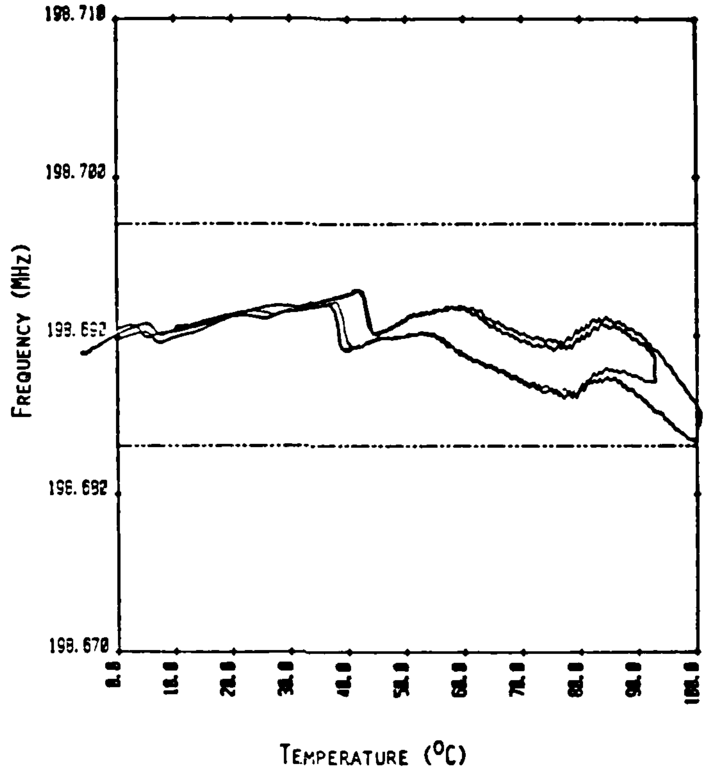

Fig. 3 Frequency deviation as a function of temperature.

3.4 Guidance System Simulation

SAW resonator has a frequency stability of one-port in 10^{10}. This number is comparable to that of the bulk wave crystal oscillators. Since the frequency counting is gated in a short time (1 to 60 s), the value of 10^{10} stability should be referred to as short-term frequency stability. SAW resonator is a strain sensor; therefore, substrate material is contributing, predominately to the device performance. Considering the temperature-stability requirement for some tactical missile applications, quartz substrate is chosen for the SAW resonator. Special orientation of quartz has temperature characteristics necessary to make temperature compensated SAW accelerometers.

Since maximum allowable material strain for quartz is 200 ppm, for working at 10 GS, acceleration input, the device performs on scale factor of 20 ppm/G. Using these data, both bit quantization and frequency scale factor can be determined.

1. Bit quantization is defined as the smallest detectable velocity at the maximum acceleration input. Considering a center frequency of 376 MHz for the SAW resonator, the bit quantization of 1.3×10^{-3} m/s is achievable.

2. Frequency scale factor is defined, a count number of bits which is equivalent to the unit of the acceleration. Considering a center frequency of 376 MHz for the SAW resonator, a frequency scale factor of 769 Hz/m/s^2 has been achieved.

Shown in Fig. 4 is the actual count output of a SAW sensor when measured by a counter with a 1 s gate time. The difference frequency of 60 kHz has been subtracted, and only the deviation in the difference frequency (± 1 Hz) is shown. Summing the counts results in the velocity count (± 10 Hz) as a function of time shown. This curve represents the area under the acceleration-frequency curve. Performing another summation as a function of time results in the curve for displacement (± 4000 Hz). The integrated velocity error for the 1000 s time period shown typically was less than 0.013 m/s, and the position error typically was less than 5.2 m. As expected, the integrated error is closely related to the integration time, and this is dependent on the actual mission time or time for which no other guidance data are available.

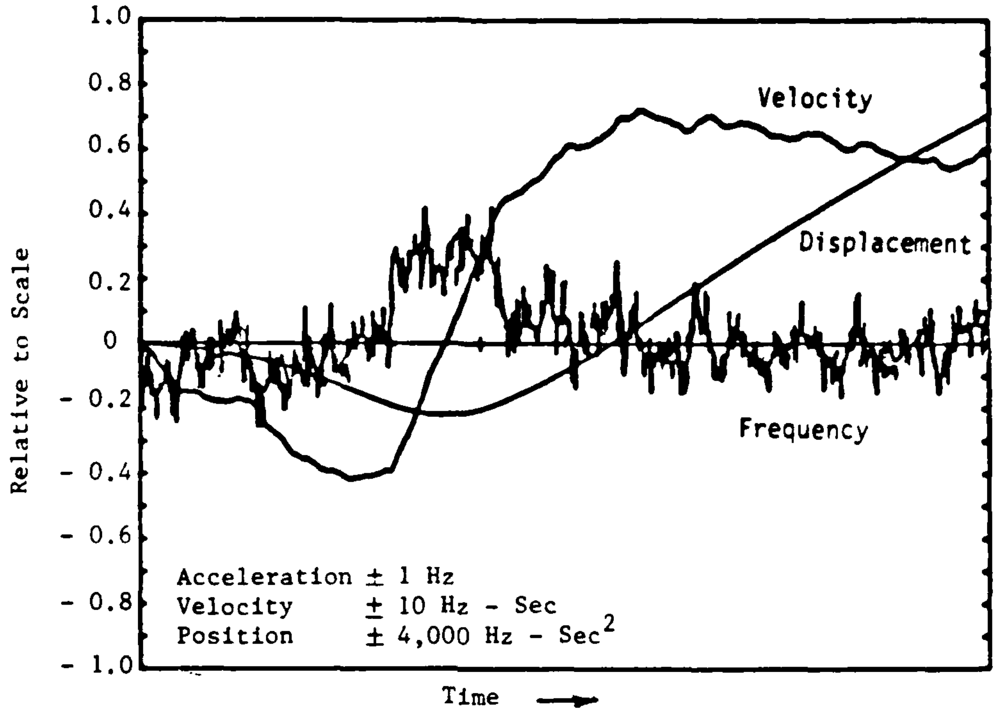

Fig. 4 Measured count output of a SAW dual crystal sensor vs time. Total time was approximately 18 min with a 2 s gate time. Also shown is the computed velocity from integrating once as well as the displacement as a result of integrating the counter output twice.

Sensor integrated errors for shorter gate and mission times were readily measured. Shown in Fig. 5 is a plot of frequency deviation, velocity error, and displacement error when the gate time is 10 m/s for 1000 counts. Theoretically this gives a data output 100 times a second. This corresponds to a velocity error of less than 0.0023 m/s and a displacement error of less than 0.042 m for a 3-min mission time.

Since the mission time was known in these tests the cumulative error per unit time for a SAW inertial sensor can be calculated. In the first test, the mission time was approximately 20 min, and the cumulative displacement error was 5.2 m, giving an error rate of approximately 15.6 m/h. In the second test the mission time was 3 min and the cumulative position error was 042 m, giving an error rate of approximately 0.84 m/h.

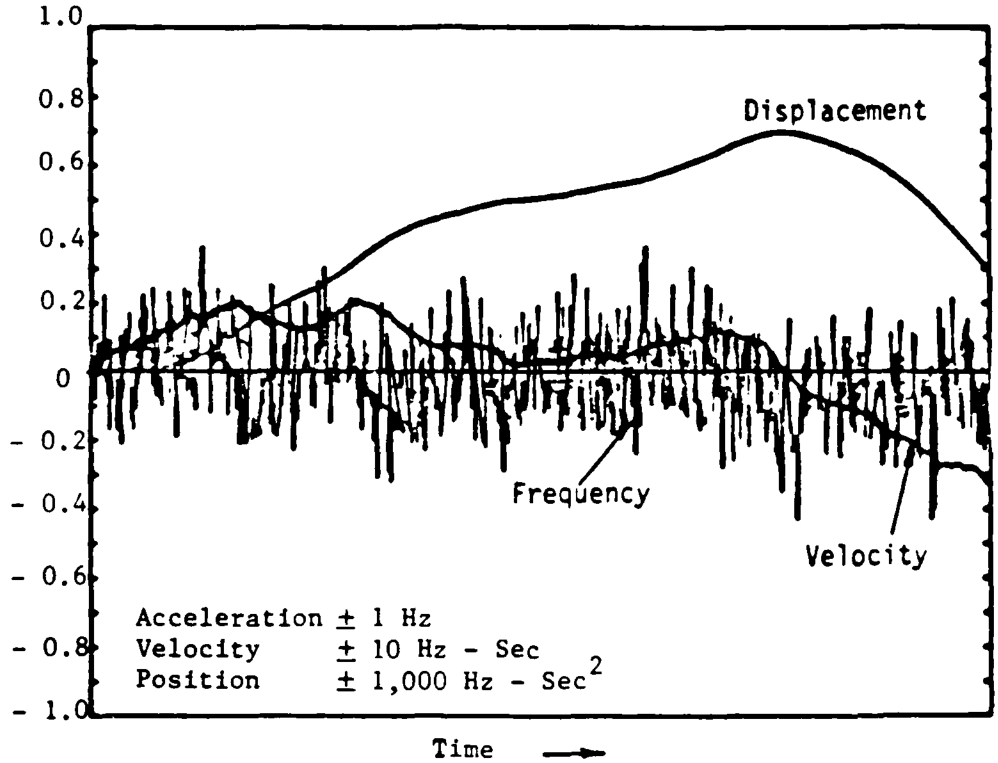

Fig. 5 Measured count output of SAW dual crystal sensor vs time. Total time was approximately 3 min with a 10 ms gate time. Also shown is the computed velocity from integrating once as well as the displacement as a result of integrating the counter output twice.

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