Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

HIGH SHOCK TCXOS FOR ADVANCED SMART MUNITIONS

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***Abstract* – A high shock (50 kG) survivable precision frequency source for use in miniature GPS receivers has been developed, enabling fast satellite acquisition in advanced gun-launched "smart" projectiles. The TCXO (temperature-compensated crystal oscillator) has demonstrated survivability through in-house gas-gun high shock testing. The critical element, the quartz crystal, has been shock-hardened, and the circuitry has been miniaturized using an ASIC.**
***Keywords*- High Shock, Temperature Compensated Crystal Oscillator, TCXO.**

INTRODUCTION

Smart munitions combine the accuracy of guided missiles with the low cost and rapid firing rate of conventional gun-launched projectiles. High accuracy is achieved in part by the use of GPS-based navigation. During launch from the gun tube, the projectile experiences a high-G shock pulse as it rapidly accelerates to launch velocity. The maximum acceleration level may be as low as 7 kG to 10 kG for older systems and as high as 50 kG or even more for advanced guns and propellants under development.

A key to guidance accuracy and high kill probability is the accuracy of the GPS receiver's clock, which determines the receiver's acquisition time. As acceleration levels increase, the allowable acquisition time becomes shorter, placing increased demands on the clock.

The TCXO developed under this effort was targeted at a specific program for which the anticipated launch pulse is 50 kG peak, with a 1 ms rise time, a duration of 7 ms, and a set-forward of 4 kG, 0.3 ms. The paper describes an ASIC-based TCXO meeting this requirement, including the shock-survivable results. As currently configured, overall dimensions are 17.5 x 12.0 x 3.5 mm (0.69 x 0.47 x 0.14 inch). A much smaller version, 7 x 5 x 2 mm (0.27 x 0.20 x 0.05 inch), is possible without major component changes. The present design allows frequencies from 10 MHz to 24 MHz without frequency multiplication or division. Anticipated enhancements could permit higher oscillator frequencies.

An important part of the program has been the development of an instrumented in-house shock-testing facility, enabling rapid evaluation of shock performance during development and production. The principal features of this facility are shown.

CRYSTAL RESONATOR

The baseline oscillator used a circular crystal blank mounted in either an HC45 or CF6 package.

Previous testing had shown that neither of these constructions was capable of withstanding the shock levels of this program. Accordingly we have developed a rectangular AT-cut resonator in a 7 x 5 mm ceramic package. As shown later, this resonator is capable of surviving the specified shock with acceptably small frequency change.

OSCILLATOR

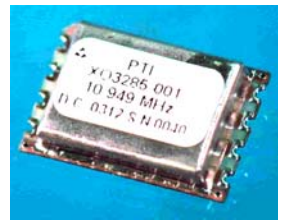

Fig. 1 Interim version of the high shock TCXO

The TCXO consists of the 7 x 5 mm resonator and a packaged ASIC plus 2 additional capacitors. An optional inductor allows for the use of crystals with a greater range of load capacitance. The current version, Fig. 1, measures 17.5 x 12.0 x 3.5 mm (0.69 x 0.47 x 0.14 inch). A much smaller version, 7 x 5 x 2 mm (0.27 x 0.20 x 0.08 inch), Fig. 2, without the optional inductor, is being constructed. Electrical and shock performance will be at least as good as the current version. Size reduction will be attained by using unpackaged ASIC die and mounting the resonator package on top of the oscillator package.

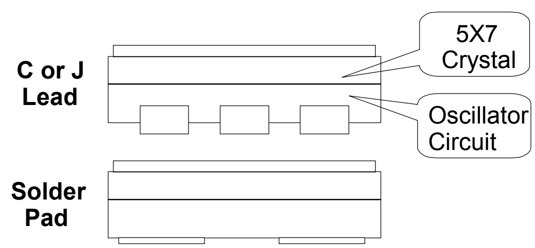

Fig. 2 Proposed 7 x 5 mm TCXO

SHOCK TESTING

Refinement of the design and verification that the design performs correctly after being subjected to the shock levels specified under this program, requires the use of a high shock test facility.

We had previously shown that centrifuge testing is insufficient to ensure resonator survivability under the condition specified for this program. Some resonators that survive high level constant acceleration in a centrifuge fail under dynamic shock conditions.

We performed shock testing at three facilities. They were the Split-Hopkinson Bar at Brown University, the 4-inch Gas-gun at ARL and a 2-inch gas-gun at PTI. A comparison of the shock pulses available at the chosen facilities is presented in TABLE 1. [1]. Prior to completing our shock tester we had some testing performed at the outside facilities.

Preliminary testing of several different resonator designs was done on the Split-Hopkinson Bar at Brown University. This facility provided short duration, bi-directional shock pulses Fig. 3. Results of this test are discussed in the resonator section.

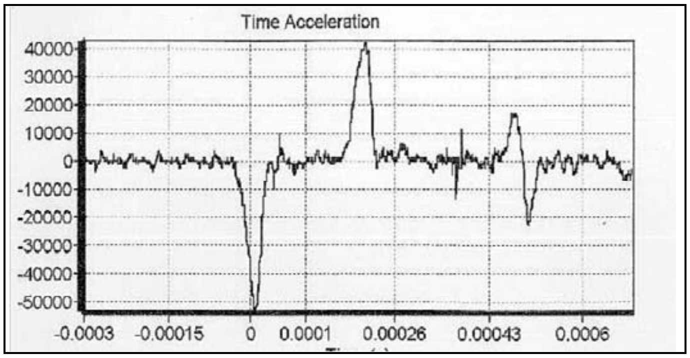

Fig. 3 Shock Pulse generated on the Hopkinson Bar

A much longer, 45 kG, 0.6 ms shock test was performed using a 4 inch gas gun at the Army Research Lab facility at Adelphi, MD.[1] Fig. 4 shows the pulse. This test also provided valuable results (detailed later)

TABLE 1 Test Facility Comparisons

	ARL Air Guns			PTI Air Gun	Hopkinson Bar	
Item	7	4	3	2	0.25	inch
Peak Acceleration	50	125	20	50	50	KG
max pulse duration	3.0 (4.0)	3	2	2	0.1	mS
max payload weight	135	10	5	1	0.05	lbs
max payload diameter	6.25	3.5	2.75	1.5	0.25	inch
max payload length	48	9 (18)	6(12)	6	0.5	inch
max spin	n/a	n/a	300	n/a	n/a	rps

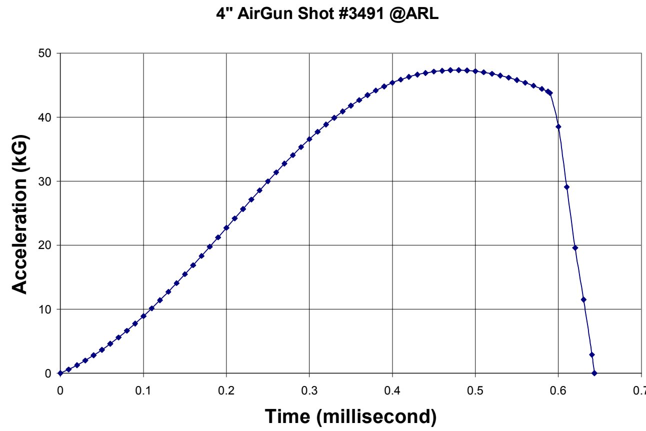

Fig. 4 Shock Pulse generated on ARL Gas-gun.

To provide the rapid turn-around necessary to test and validate design iterations, and to provide on-going screening of production samples, we constructed a 50mm (2-inch) gas gun at PTI, Fig. 5. The gun first accelerates the test projectile to obtain a high velocity and then rapidly decelerates over a distance of up to 1 meter to obtain the desired shock pulse. The initial velocity is determined by the projectile mass, the gas pressure used and the distance over which the projectile is accelerated (which we hold constant at 18 m (60 feet)). The retarding material (the mitigator) and the shape and mass of the projectile set the deceleration pulse rise time and magnitude. Fig. 6 shows a projectile and mitigator after firing. The velocity sets the duration of the shock pulse and is measured using an array of photodiodes located just in front of the mitigator. We use a variety of materials for the mitigator depending on the shock pulse required. The material crush constants were measured to aid in the choice of material. The on-board shock recorder enables the shock profile of different mitigator formats to be characterized. Subsequent runs can then be made without the recorder, increasing the payload.

1 The pulse level was calculated from a measurement taken on the target.

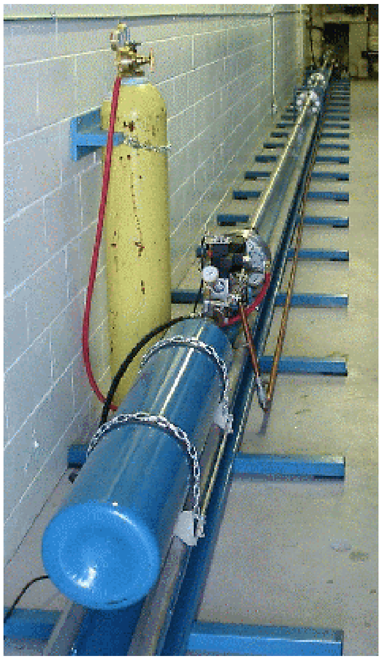

Fig. 5 PTI Gas Gun

Fig. 6 Projectile Retarded in Mitigator

We have obtained velocities up to 2000 m/sec and shock pulses of up to 50-kG peak with a duration of 1 ms. The test projectile has been instrumented by the addition of an on-board accelerometer and recorder, Fig. 7.

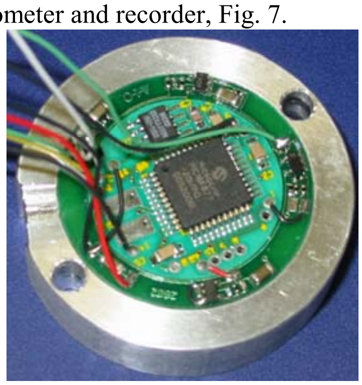

Fig. 7 On board data recorder

A typical pulse is shown in Fig. 8. The cause of the ringing in this example has not been determined and further investigation is required. As a result of survivability issues with the accelerometer, we have not been able to record shock levels up to the full capability of the gun. Despite being calibrated by the manufacturer to 60 kG with a times 3 over-shock rating accelerometers were destroyed in initial tests. Suspecting that the initial rise time was causing overstress, we mounted the accelerometer in a pliable material for subsequent tests. We have had no additional accelerometer failures. Some failures were seen in the batteries used to power the recorder. We are investigating modified mounting of the batteries. To determine the shock level at higher levels we calculate the shock value based on the incident velocities and stopping distance in the mitigator of the projectile. Scaling the shock levels seen at lower levels would result in much higher peak levels than the average level.

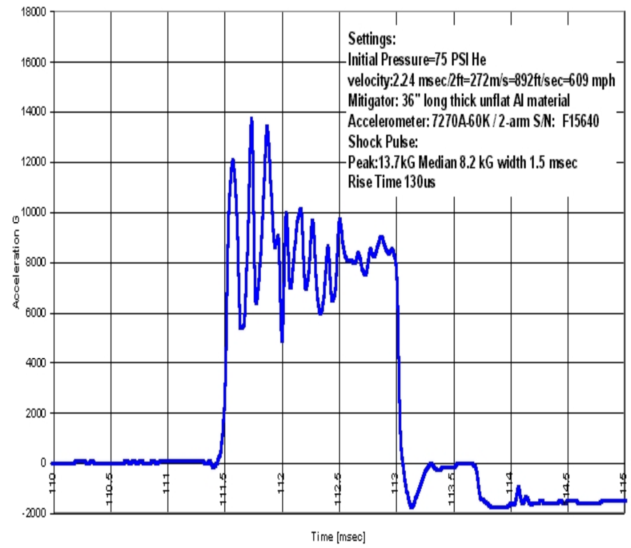

Fig. 8 Typical Shock Pulse for the PTI Gas Gun.

The test devices are typically potted using wax into cavities in an aluminum disk, Fig. 9. It is important that the supporting scheme does not result in additional force applied to the test article; even a few mm of wax exert a considerable force when accelerated at 50 kG.

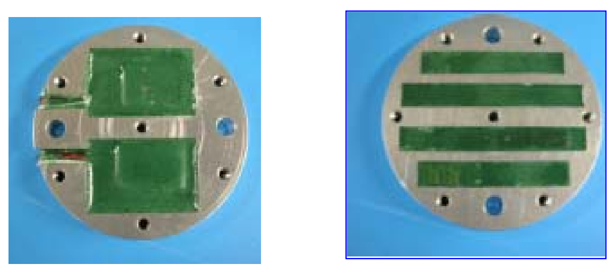

Fig. 9 Test articles potted in aluminum disk

With the gas gun we have performed many tests with successful results. In addition to its value as an engineering tool, having this facility in-house will allow us to perform screening tests on production units to ensure that process controls are working as desired.

RESULTS

Resonator Short Duration Shock Test

We initially arranged a test for shock performance on a Split-Hopkinson Bar. Tested were resonator designs developed at PTI together with resonators obtained from other sources. Eight different groups were tested. Within the groups there were variants related to the connection and mounting method. A total of 23 different types were tested. For each type, between 2 and 5 resonators were tested. Many of the resonator designs survived, some with small frequency shift. Most of the resonators we tested were not intended for use in a TCXO and consequently were not designed to be tunable as is required for a TCXO. For the applications we are initially targeting, a frequency of approximately 10.9 MHz is required. That requires a resonator design with higher motional capacitance than was available in the smaller out-sourced resonators.

Resonator Long Duration Shock Test

A long pulse test was performed at the ARL facility. Both oscillators and resonators were tested. The resonator test results are given in TABLE 2

A four inch Air Gun was used to generate a shock of 47 kG peak amplitude, 0.6 ms total duration with > 45 kG for 0.2 ms. The shock is uni-directional. Most groups of the out-sourced resonators had failures and frequency shifts of 0.7 ppm to 10 ppm except one unit that shifted by 174 ppm. A group of custom resonators had failures for some designs and frequency shifts of 0.18 ppm to 250 ppm. For the E5 resonator group there were no failures and frequency shifts were < 0.7 ppm

Shock Tests of Oscillator

Long duration shock testing of Oscillators was also performed at the ARL facility. The shock pulse was the same as for the resonator test. The results are summarized in TABLE 3. Models XO3022-036 & XO3085-002 are TCXOs that use an initial resonator design. XO 3085-002 is the intermediate size built with discrete components. HGXO is a clock oscillator using a strip type resonator. The TCXOs containing the initial resonator design at 43 MHz & 47 MHz had no failures but shifts 1.5 ppm to 14 ppm A custom non-tunable clock oscillator (non-TCXO at 20 MHz) had no failures and frequency shifts <0.7 ppm. Dummy TCXOs with potting showed no visible damage, while those without potting were crushed, Fig. 10

Fig. 10 Crushed TCXO

TABLE 2 RESULTS OF LONG DURATION RESONATOR SHOCK TEST

Resonator Group	Frequency kHz	No units	No Reading qty	Median (ppm)	Mean (ppm)	Maximum (ppm)	Minimum (ppm)	STDDev (ppm)
A-1	43796	2	0	6.85	6.85	9.11	4.59	3.20
A-2	10947	10	0	14.34	14.68	27.22	3.65	7.65
A-3	47031	7	0	1.15	10.64	38.36	0.89	15.56
B-1	11057	3	3		none	survived		
C-1	11057	10	6	1.72	1.92	3.62	0.63	1.24
B-2	19996	10	1	2.10	21.10	173.63	0.75	57.21
B-3	19193	6	0	1.09	3.75	10.42	0.73	4.41
C-2	19997	6	3	3.38	3.73	7.60	0.35	2.53
D-1	19999	2	0	10.68	10.68	13.70	7.65	4.28
E-1	10946	2	0	12.15	12.15	22.57	1.74	14.73
E-2	21889	2	2		none	survived		
E-3	43797	1	1		none	survived		
E-4	10946	6	4	137.76	125.35	250.51	0.18	177.01
E-5	47032	7	0	0.21	0.32	0.74	0.04	0.23

TABLE 3 RESULTS OF LONG DURATION OSCILLATOR SHOCK TEST

	Frequency kHz	No units	No Reading qty	Median (ppm)	Mean (ppm)	Maximum (ppm)	Minimum (ppm)	STDDev (ppm)
XO3022-036	43798	3	0	10.73	9.55	13.41	4.50	4.57
XO3085-002	47033	3	0	2.75	3.32	5.75	1.45	2.20
HGXO	20000	3	0	0.51	0.38	0.58	0.05	0.29

Shock Test of ASIC-based TCXO.

PTI's ASIC-based TCXO was tested at PTI in our gas gun. The average acceleration, based on the initial velocity and the stopping distance, was 45 kG.[2] The oscillators survived with no visible signs of damage and performed as before the shock. As detailed in TABLE 4, they had frequency shifts of 1.02 ppm to 2.18 ppm. Control units measured at the same times had shifts of approximately –0.2 ppm. Units 218 and 229 were built without an inductor; they showed the least change. From this limited data we suspect that the inductor value changed during shock and should be omitted from the circuit if possible.

TABLE 4 RESULTS OF SHOCK TEST ON NEW TCXO

Serial Number	218	224	229	241	251
Pre-shot Frequency (ppm)	-0.2	0.09	0.08	-0.13	-0.01
Post-shot Frequency (ppm)	0.82	2.27	-1.35	-1.56	-1.94
Frequency Shift (ppm)	1.02	2.18	-1.43	-1.43	-1.93

FUTURE WORK

Additional effort is being applied to refine the measurement of the shock pulse. Further TCXOs are being assembled as additional new resonators are completed. Further work is required to finish packaging the oscillator in a 7 x 5 x 2 mm form factor. Certain refinements to the resonator have been identified that are expected to reduce the frequency shift from shock.

SUMMARY

A miniature, high shock TCXO has been developed that will meet the requirements of advanced smart, gun-launched munitions with launch pulse levels up to 50 kG. With a low-risk additional packaging effort, an overall size of 7 x 5 x 2 mm can be achieved.

REFERENCES

1 Ami Frydman , "Ballistic Simulation Capabilities & Technical Support Review", unpublished.

2 To date we have been unable to measure this level of shock using the on-board accelerometer. Scaling the pulse measured at lower levels suggests that the peak level is approximately 70% higher than the average level or 76 kG. We are planning to repeat the test, with the on-board accelerometer replacing the oscillators, to get a measurement of the true shock pulse.