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Air-Deployable Geophysics Package

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Air-Deployable Geophysics Package

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Introduction

We are using Lawrence Livermore National Laboratory's (LLNL's) diverse expertise to develop a geophysical monitoring system that can survive being dropped into place by a helicopter or airplane. Such an air-deployable system could significantly decrease the time and effort needed to set up such instruments in remote locations following a major earthquake or volcanic eruption. Most currently available geophysical monitoring and survey systems, such as seismic monitoring stations, use sensitive, fragile instrumentation that requires personnel trained and experienced in data acquisition and field setup. Rapid deployment of such equipment can be difficult or impossible. Recent developments in low-power electronics, new materials, and sensors that are resistant to severe impacts have made it possible to develop low-cost geophysical monitoring packages for rapid deployment missions.

In this proof-of-concept study, we focused on designing a prototype with which we could test key components of an air-deployable system to determine overall feasibility. Our strategy was to focus on low-cost battery-powered systems that would have a relatively long (several months) operational lifetime. We concentrated on the conceptual design and engineering of a

single-component seismic system that could survive an air-deployment into an earth material, such as alluvium. Actual implementation of such a system is a goal of future work on this concept.

For this project, we drew on the many years of research and experience available in LLNL's Earth Sciences Department, Radio Shop, Plastics Shop, and Weapons Program. Our Earth Sciences personnel brought a broad range of geophysical research experience to this study, and their recent work with advanced geophysical sensors was also helpful. The Radio Shop has extensive experience in designing telemetry systems similar to those needed for this project. Our Plastics Shop helped devise and mix the potting material used to surround and protect the sensors and electronics. The expertise of our Weapons Program in designing earth and hard-structure penetrator weapons provided us with valuable information on the techniques required to make standard electronic circuits and components survive high impact forces.

The military has had several programs to develop air-deployed and cannon-deployed seismometers. Recently, a sonobuoy manufacturer has offered an air-deployable geophone designed to make relatively soft landings.

Development of a Prototype Air-Deployed System

As shown in Fig. 1, a complete air-deployable geophysical monitoring system consists of a sensor, data acquisition circuitry, a microcomputer with solid-state memory, a radio transmitter, and an antenna deployed in a penetration package. The instrument detects events and transmits (1) a radio signal to indicate that an event has occurred and (2) the raw data from this event. The analog-to-digital converter (A/D), microcomputer, and memory were not included in the prototype instrument to reduce the scope of the test and make it much more affordable with a minimal loss in significance. We felt that if the prototype electronics (particularly the radio

transmitter, batteries, and sensor) survived the tests intact, there was reason to believe that these additional components would also survive.

Expected Deceleration Forces

Experience in the munitions area¹ has shown that the maximum deceleration experienced by a free-falling object hitting the earth's surface is from 500 to 3000 g, depending on the type of material impacted. This compares to deceleration forces of over 100,000 g for rocket or explosively propelled penetrating munitions. The deceleration time, or pulse width, is highly

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Figure 1. Complete prototype air-deployable geophysical monitoring system.

dependent on the earth material impacted. Survivability depends on the pulse width as well as the peak acceleration.

To survive these deceleration forces and the rebound forces after the instrument impacts the ground, the package must be designed for both positive and negative accelerations, although the rebound forces are smaller in amplitude and pulse width than the deceleration forces.

Case Design

The first step in ensuring survival is to make sure that the case will not be catastrophically deformed on impact. Some deformation is inevitable, but this need not be a problem as long as the amount of deformation is anticipated and the electronics package inside of the case is designed to tolerate such deformation.

One LLNL Weapons Program project had 12 case failures in their first 12 experiments.² At this point, they decided to use computer modeling to determine the cause of these failures. Using the DYNA2D code, they simulated a number of different designs so that they could determine just how the cases were failing. Once they had a design that survived in the computer simulation, they conducted another experiment, and the case survived with deformations that were within 2 mm of those predicted by the model.

Before we field test a complete air-deployable instrument package, we will need to run simulations of our case design. We should also model impacts at different velocities, into different soils, with various entry angles. To keep costs down for this proof-of-concept demonstration, we based our case design work on the experience of the weapons designers. We also used

standard aluminum tubing for the case to minimize the production costs (Appendix A).

Component Encapsulation

One way that electronic components can survive extremely high impact is to completely encapsulate them with a potting compound. Once again, we were able to apply the long-term experience and developments of the LLNL Weapons Program to our project. The potting compound³ (MEL80-001500) and potting system that the weapons designers have developed allows standard electronic components to survive virtually any impact that the designers can generate. Part of this potting technique is ensuring that there are no voids because components *will* break off and move into voids under strong deceleration or acceleration. This potting technique does not prevent the movement of components, because things *will move* under strong deceleration or acceleration, but it does ensure that everything moves as a unit.

Discrete components must be mounted with a 0.5-cm stand-off distance from the circuit board so that the potting compound can flow under the component and not leave a void. Integrated circuit leads are not long enough for this treatment, so a piece of circuit board material is placed under the integrated circuit to eliminate any voids between the integrated circuit and the circuit board.

Connectors can be used if needed. The air space in the connector is filled with silicon grease to prevent voids. When disassembling, this grease is heated with hot air and then the liquid grease is poured off. Our system uses a connector at the top to allow for diagnostics and to recharge the batteries. This connector is filled with grease prior to tightening down the top of the case.

Strong deceleration can cause the conductor in insulated wire to slip down inside its insulation, which causes the wire to stretch and break at the top end. This can be avoided by tying a knot in the wire to prevent the wire from slipping.

The circuit boards, batteries, and sensors must be fixed in their proper place while the potting compound is pumped into the case or mold. One way to do this is to use printed circuit board material with holes in it for the batteries and use solid wire between the boards to hold them in proper relation to each other (Fig. 2). Once the potting compound has cured, the boards and wires serve no structural purpose.

Prior to potting, the electronics are dipped in a "conformal" coating. We used Dow Corning 1-2557 conformal coating. This coating is less viscous than the potting compound, so it can fill in some tiny voids that would otherwise not be filled. The major purpose of the conformal coating is to provide a buffer between the circuit and the potting compound. The difference in the coefficient of thermal expansion between the circuitry and the epoxy is sufficient that the epoxy will crush the circuitry during temperature cycling. A conformal coating that is 0.075 to 0.250 mm (0.003 to 0.010 in.) thick should be used. Unused holes in the printed circuit board should be checked to make sure that the conformal coating does not create any trapped air pockets in the hole. If there is a trapped air pocket, the bubble is cut away so that the potting material can get in. Alternatively, the holes can be filled with solder before adding the conformal coating; this should be done if access to any circuit board is restricted.

The LLNL Plastics Shop of the Material Fabrication Division⁴ potted our unit by mixing the syntactic foam, removing air bubbles from the mix by placing the material in a vacuum chamber, pouring the foam into our case, and then lowering the electronics package very slowly into the case.

The electronics are potted so that the block of material is about 0.5 mm taller than the interior of the case. This is done by putting a shim between the body and the top of the case. The shim is removed after the potting compound is cured. When the case is tightened down at closure, the block of potting compound is compressed, which helps eliminate small voids between the potting compound and the case.

Sensor

We surveyed the market to find a high-impact-resistant microaccelerometer. The device that we selected is a silicon microaccelerometer that is tested and certified to withstand a 10,000-g impact on any axis (Entran EGAXT-5). This sensor has a sensitivity of 2.5 mV/g when used with a 5-V supply, and it has a flat frequency response from dc to 150 Hz.

There is also a geophone available from Oyo Geospace that will withstand 5000-g shocks, but its frequency response at low frequencies makes it inadequate for some applications.

Figure 2. Prototype of an air-deployable geophysics package.

Electronics

An important consideration in choosing electronic components for an air-deployed geophysics package is low electric-power consumption. Our system will be used in areas where access is extremely difficult, so once the battery power is used up, the instrument is lost. Consequently, most of our effort in the design of the electronics has been aimed at maximizing system lifetime by reducing electrical power consumption so that the package can operate for several months. Ensuring that the electronic components can survive the ground impact is also important, but is fairly well understood, and most components can be made to survive severe impacts.

The two largest power consumers are the seismic sensor and the radio transmitter. The sensor is the most critical of the two because it must be powered continuously. The radio can be turned off when it is not being used. A silicon microaccelerometer sensor is modeled as a resistive bridge circuit, where the resistor values change as a function of acceleration. The current through the bridge is a constant 2.5 mA at 5 V. It is difficult to get a low noise 5-V voltage source that does not consume a lot of additional power. The voltage source that we used is a compromise between low noise and low power, with the power consideration being more important. We hope that a microgeophone being developed by the Microelectronics Laboratory in LLNL's Engineering Research Division⁵ might also work for this application. This microgeophone generates a voltage in response to an acceleration so it does not require a constant current. This would reduce the present battery requirements by more than half.

The analog electronics are implemented with micropower op-amps and comparators (Appendix B). All of the analog electronics, other than the sensor, draw less than 300 μ A. Large value resistors and high input impedance CMOS electronics reduce the power consumption. This makes the system more sensitive to electromagnetic

interference, but the metal case can help protect the electronics from such interference if it is connected to the electrical ground of the circuitry.

The digital electronics are implemented using CMOS devices and will run even when the battery voltage drops below 3 V. The devices are powered directly by their own batteries without any voltage regulator.

The radio used for this proof-of-concept device is a simple transmitter that is turned on by a CMOS voltage level. This allows the digital electronics to send out pulse code signals; however, the transmitter consumes virtually no power when it is not transmitting. The radio was made for us by a company that makes animal tracking radios.

It is important for the radio transmitter not to leak rf energy inside the case. This happened during some of the testing prior to potting. The rf affected the input stage of the analog section, despite the fact that the analog component is not rated for such high frequencies. The final version of the circuitry employed a metal case around the transmitter.

We also had help from LLNL's J Division in developing a small transmitter that is capable of sending either AM or FM signals. This transmitter was not used in our initial tests, but was built to determine if such a radio (1) could be made in a manner that would allow low-power standby operation and (2) could be constructed with the potting techniques discussed earlier. Both of these goals were achieved.

Most of the LLNL radio is a single chip transmitter and an rf amplifier chip. The chips can be powered down when not in use to save power. When powering up, the transmitter chip is turned on 30 ms before the amplifier chip because it takes a few milliseconds for the transmitter chip to stabilize on the proper transmitter frequency. As soon as both chips are powered up, data transmission can start.

Tests and Results

We used existing experimental facilities at LLNL to test the survivability of the prototype. First, it was drop tested at a facility that allows a 3 m (10 ft) drop onto felt pads that tailor the deceleration impulse width. The measured impact from this test was a 950-g pulse, 2 ms wide at

the 10% point (Fig. 3). There was no noticeable effect on the instrument from this test, and it continued to function perfectly. Figure 3 shows the deceleration waveforms recorded by three accelerometers that were external to the instrument. Waveforms 1 and 2 are from sensors attached to

the adapter plate that connects the experiment package to the drop test apparatus. Waveform 3 is from a sensor glued to the top of the prototype.

The waveform shown in Figure 3 is 25.6 ms long. The impact deceleration pulse was about 2.4 ms wide with a peak amplitude of 940 g. The high frequency spike in waveform 3, just after the main deceleration pulse, is presumably due to a shock wave reflected off the bottom of the prototype case. It is also obvious that the top of the case is exposed to much more oscillatory motion than the bottom of the case, with several peaks greater than ± 400 g, while the bottom of the case experienced no oscillatory peaks of even 200 g.

Future Enhancements

There is beginning to be a surge of components designed to run off a 3-V power supply. This is driven by the laptop personal computer market, but it is to our advantage. Many of the 3-V components consume one-third the power of the 5-V components. This means that we can design more sophisticated electronics for the same amount of battery power, use fewer batteries, or ensure that the system survives longer using the present batteries.

Since this is the first high impact project at the LLNL in 12 years, modern integrated circuit packaging has never been tested. It would be highly desirable to test the existing potting techniques with surface mount electronic components. These packages consume about one-fourth the area as equivalent standard components, so smaller packages can be made or more circuitry can be included in existing packages. Testing of surface mount components should be a high priority.

We also tested the prototype on an elastic-band-accelerated drop tower. The first drop with this tower had a 3000-g impact (Fig. 4), which the instrument survived completely. The second drop had a 4500-g impact (Fig. 5), and resulted in our first electronics failure. Since there were several test points available on the connector on the electronics board, we were able to determine that the damage was to the comparator section. This is not a critical part of the electronics; in fact, it will not be included in future versions. The final drop had a 5700-g impact (Fig. 6), and all electronics survived except the already failed comparator section.

In the prototype, the data telemetry was extremely crude. Given more time and resources, we could design an FCC-approved radio capable of transmitting actual data.

We would also like to verify the case design using computer modeling to simulate impact into different rocks/soils. The Weapons Program found that computer modeling was the best way to ensure that designs worked as planned. They had numerous failures of their hardened munitions until they started modeling the mechanical design.

We would also like to test less expensive accelerometers to determine their impact tolerance when potted in syntactic foam. The foam is rigid enough to provide good coupling at seismic frequencies, but the foam will still provide some cushioning for strong impacts.

Conclusions

We have developed a prototype geophysics data acquisition system that can withstand the impact of being dropped from an airplane or helicopter without a parachute. In laboratory tests, the sensor, batteries, and analog and digital electronics survived the maximum credible impact that is expected during such an air deployment.

The digital electronics were designed to minimize electric power consumption. Once on the

ground, the device would draw such a small amount of power that it could survive for several months. In laboratory tests, this electronics package has run continuously for several months on a pair of D-cell alkaline batteries.

We have also developed a very simple and inexpensive case design. This case, created from stock aluminum tubing, survived two types of laboratory impact testing under forces that ranged from 950 to 5700 g.

Test Spec : Impact, 1000 g's, 2ms pulse

	Ch # 1	Ch # 2	Ch # 3	
Transducer Output	2000 g's/Volt	2000g's/Volt	2000g's/Volt	/Volt
Filter Freq. (-3 dB)	U/F	U/F	U/F

Results

CH	TIME	CUR AMP	PEAK AMP	1ST INT	2ND INT	TIME BASE	EXP
1	2.457mS	-70.31 g's	-945.3 g's	-408.3 In/s		25.6mS	2
2	2.355mS	-93.75 g's	-937.5 g's	-425.0 In/s		25.6mS	2
3	2.150mS	101.5 g's	-1023. g's	-390.7 In/s		25.6mS	2

Remarks

June 9, 1993. Seismodart Impact Test. Test ID # 2947.
 Real Test drop from 10ft., 1.32 in. of felt programming material.
 (3) 2225 accel's. 2 located on seismodart adapter plate and 1 on top of seimo
 dart top. (Test is called run 4 on tape)

Figure 3. The prototype of an air-deployable geophysics package was drop tested at a facility that allows a 3 m (10 ft) drop onto felt pads that tailor the deceleration impulse width. The measured impact from this test was a 950-g pulse, 2 ms wide at the 10% point. The deceleration waveforms were recorded by three accelerometers that were external to the instrument.

Test Ident: GHI TEST LAB

Measurement Constants:

	Ch # 1	Ch # 2
Transducer Output	5000 g's/Volt	10000g's/Volt
1st Integral Sealer	386.4	386.4
2nd Integral Sealer	1	1
Filter Freq. (-3 dB)	3000 Hz	U/F

Remarks Filtered at 3 kHz
5 ft 2 in. drop

Figure 4. Waveforms from an elastic-band-accelerated drop-tower test during which the prototype survived a 3000-g impact.

Test Ident: GHI TEST LAB

Measurement Constants:

	Ch # 1	Ch # 2
Transducer Output	10000g's/Volt	100g's/Volt
1st Integral Scaler	386.4	386.4
2nd Integral Scaler	1	1
Filter Freq. (-3 dB)	5000 Hz	U/F

Remarks 7 ft 2 in. drop

Figure 5. Waveforms from an elastic-band-accelerated drop-tower test during which the prototype experienced a 4500-g impact and had damage to the electronics to the comparator section.

Test Ident: GHI TEST LAB

Measurement Constants:

	Ch # 1	Ch # 2	Ch # 3	Ch # 4
Transducer Output	10000g's/Volt	10000g's/Volt	100g's/Volt	100g's/Volt
1st Integral Scaler	386.4	386.4	386.4	386.4
2nd Integral Scaler	1	1	1	1
Filter Freq. (-3 dB)	2000 Hz	5000 Hz	U/F	U/F

Results

CH	TIME	CUR AMP	PEAK AMP	1ST INT	2ND INT	TIME BASE	EXP
1	947.2uS	468.7 g's	5703. g's	1088. In/s		6.4mS	8
2	678.4uS	-1093. g's	-5625 g's	-976.8 In/s		6.4mS	8

Remarks 8 ft 6 in. drop

Figure 6. Waveforms from an elastic-band-accelerated drop-tower test during which the prototype experienced a 5700-g impact; all of the electronics survived except the comparator section that failed in the previous 4500 g test (Fig. 5).

Acknowledgments

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Appendix A

Prototype of an air-deployable geophysics package,
using standard aluminum tubing for the case

Analog electronics wiring diagram for the prototype of an air-deployable geophysics package

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