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An Explosive Acoustic Telemetry System For Seabed Penetrators

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An Explosive Acoustic Telemetry System
For Seabed Penetrators

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ABSTRACT

This report discusses the design and past applications of an explosive acoustic telemetry system (EATS) for gathering and transmitting data from seabed penetrators. The system was first fielded in 1982 and has since been used to measure penetrator performance on three other occasions. Descriptions are given of the mechanical hardware, system electronics, and software.

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1. INTRODUCTION

This report discusses the design and use of a unique telemetry system developed by Sandia to transmit data from extreme ocean depths. The basis of the concept is found in the work of Edrington (1984), in which he describes the use of strong acoustic signals generated by explosive charges to encode and transmit information. A telemetry system based on this principle was built, and several generations have been fielded on board seabed penetrators. In the discussion that follows, we describe the historical use of this system and the principal elements of the hardware and software.

Three types of telemetry systems (Figure 1) have been developed and used by experimenters to obtain data from instrumentation onboard seabed penetrators. Sandia pioneered the development of trailing-wire techniques and explosive acoustic telemetry and has used the acoustic Doppler method.

Sandia began employing instrumented seabed penetrators during the late 1960s as an outgrowth of its studies of terrestrial soil penetration by air-delivered weapons (Young, 1967, 1972). The first sea tests were conducted in 1970 as part of the Marine Sediment Penetrator Program. Small vehicles measuring 3 in. in diameter and weighing 100 lb were developed for obtaining an approximation of the strength versus depth properties of seafloor sediments by measuring the decelerations accompanying burial (Colp et al., 1975). These penetrators carried an onboard accelerometer and transmitted analog data back to the surface vessel via a trailed-wire link (Figure 1). Allowable water depths were limited by the design to a few hundred meters, and actual penetrations were less than 5 m. This telemetry method was later adopted by the French Commissariat a l'Energie Atomique and extended to waters approaching 6000 m deep and to sediment penetrations of over 30 m (Hembise et al., 1987; Hickerson et al., 1987).

Figure 1. Common Methods for Telemetering Data from Seabed Penetrators: (a) Trailed Hard Wire, (b) Acoustic Doppler Shift, (c) Explosive Acoustics.

In the mid-70s the Naval Civil Engineering Laboratory expanded on the use of penetrators for measuring sediment strength. The acoustic Doppler method for measuring relative velocities was implemented for this purpose to obtain a record of penetrator flight dynamics. The signals from a fixed-frequency transmitter mounted in the penetrator tail were monitored by hydrophones near the launch site, and shifts in the observed frequency were related to actual velocity (Beard, 1977, 1981). Burial decelerations were then related to soil strength through models developed for this purpose. Although Sandia has employed this method (Freeman and Burdett, 1986; Hickerson in ENEA, 1987), the Building Research Establishment of the Department of the Environment in the United Kingdom has been the principal user in recent years. They applied the method to large penetrators launched in waters over 5000 m deep to measure water flight velocities and penetrations of over 50 m (Freeman and Burdett, 1986; Freeman et al., 1987).

The third method for collecting and transmitting data from deep water, explosive acoustic telemetry, is embodied in the Explosive Acoustic Telemetry System (EATS) (Calloway, 1984a, 1984b). EATS solves the problem of transmitting acoustic data from great depths and from large sediment overburdens by providing a very strong and unequivocal transmitted signal. Although EATS is inherently limited in the amount of information it can encode and transmit, this method has been successful.

EATS uses pulse-position modulation to encode and transmit data previously collected at 800 Hz by a microprocessor and stored in memory. The microprocessor initiates transmission of selected portions of the data by controlling the operation of a fire set. This fire set detonates explosive charges, typically weighing about 500 mg and located in a ring segment of the penetrator body (Figure 2). The time interval between two consecutive detonations is encoded to contain the information of two 6-bit digital words or one 16-bit digital word. The resulting acoustic pulses, such as those in Figure 3, are received by hydrophones deployed near the surface and are tape-recorded for later decoding.

Several versions of EATS have been deployed since its inception. This report concentrates on the final version used to gather penetrator data

Figure 2. The Instrumented Seabed Penetrator, Model ISP-3, Carrying the Explosive Acoustic Telemetry System.

Figure 3. Typical Acoustic Pulse Waveform Generated by Two Consecutive EATS Detonations.

during the Tyro-83 campaign to the Nares Abyssal Plain in the Atlantic (Freeman and Burdett, 1986) and the ACIS campaign in the Mediterranean (Hickerson in Boisson, 1986). This version of EATS samples the output of an axial accelerometer at 800 Hz and stores these data in a 30-s circular memory that is overwritten once it fills. After sensing a deceleration greater than a threshold level, the unit declares that impact has occurred and permanently stores the previous 5 s of data and all that follow until the penetrator comes to rest. Afterwards, an onboard algorithm integrates the deceleration data to obtain the impact velocity and penetration depth. These data, along with 26 equally spaced deceleration measurements, are transmitted by the telemetry system.

2. SUMMARY OF PAST APPLICATIONS AND TESTS

EATS has been fielded on four previous occasions in the Instrumented Seabed Penetrator (ISP) series of experiments:

- 1982 ISP-1: A gun-launched vehicle was fired into sediments in the Gulf of Mexico near the Mississippi Delta to provide the first operational test of EATS (James, 1983).
- 1983 ISP-3: Two freefall penetrators of this design were launched in 1700 m of water off the California coast from Naval Civil Engineering Laboratory facilities near Port Hueneme to test an improved version of EATS and to obtain data on penetration performance (Talbert, 1984).
- 1983 ISP-4 (also called Type 7 and 8 in some reports): Four freefall penetrators were launched in 5800 m of water over the southern Nares Abyssal Plain north of Puerto Rico as part of the Seabed Working Group Tyro cruise of 1983. These vehicles gathered data on penetrator velocity and penetration performance (Freeman and Burdett, 1986).
- 1986 ISP-4: Two freefall penetrators were launched as part of the ACIS Campaign of the Seabed Working Group to test methods for obtaining measurements on the closure of the entry paths of penetrators (Hickerson in Boisson, 1986).

ISP-1, a vehicle weighing 320 kg, was developed to test the explosive acoustic telemetry concept and the first version of the hardware (James et al., 1981; James, 1983). The penetrator was a finless body, 0.20 m in diameter by 2.4 m long. The onboard EATS carried a single accelerometer and instrumentation that could calculate the penetration depth based on acceleration measurements. After the penetrator came to rest, EATS

transmitted the depth measurement four times by means of eight detonations (Calloway, 1984a). Pairs of charges contained different amounts of explosive to test the effect of this variable on signal strength. ISP-2, a similar penetrator with a recoverable instrumentation and memory package, was launched nearby to verify the performance of ISP-1. Each penetrator was fired in water 22 m deep. A propellant charge weighing 1.6 kg gave ISP-1 an estimated muzzle velocity of about 50 m/s and produced an EATS-measured penetration of about 28 m, well within the range of predictions for the sediment being penetrated. ISP-2 was propelled by a charge weighing 3.2 kg and achieved a muzzle velocity of 90 m/s and a penetration of about 36 m. We believe the results for ISP-1 and ISP-2 were consistent with design predictions and that each demonstrated the viability of the separate telemetry methods.

Signal characteristics from ISP-1 and the propagation of sound through the sediment and water column were later analyzed by Calloway (1984a) and Edrington and Calloway (1984). Charges of less than 100 mg of explosive produced weak signals exhibiting a low signal-to-noise ratio. Charges of about 500 mg produced strong, easily detected signals and high signal-to-noise ratios. The very gassy sediments of the Gulf greatly reduced the sound velocities in the sediment, and the penetration depth estimated from the measurements of sound velocity was about 6 m less than that measured by EATS. No conclusions were drawn from this comparison, although the nature of the EATS measurement would tend to make it more accurate than the depth of penetration estimated from the measurements of sound velocity.

Two penetrators of the ISP-3 design were launched in 1700 m of water to test an improved version of EATS and the penetration achievable by a freefall vehicle (Talbert, 1984). Each penetrator weighed 445 kg and measured 0.20 m in diameter by 3.3 m long. The version of EATS carried by ISP-3 contained eight 500-mg charges. A test charge was detonated immediately before launch to signal system operation. After launch, four timed charges were detonated to allow calculating distance and velocity from the arrival times of the signals and the speed of sound in seawater. After coming to rest, EATS detonated three more charges that transmitted the encoded data for its measurements of impact velocity, peak deceleration during penetration, and penetration depth.

Both launches of ISP-3 were successful, and EATS measured 11 m and 12 m penetrations respectively (Calloway, 1984b). Before these experiments, the accelerometer and microprocessor packages from each unit were calibrated by simulating the expected deceleration profile on Sandia's sled track at Area III. After calibration corrections, each penetrator was found to have impacted at 37 m/s, achieving depths of 11 m, and experiencing peak decelerations of 17 g. These procedures for sled track calibration and later adjustment of the recorded data became standard and were used during all later deployments of EATS.

Calloway (1984a) analyzed the signals received during the ISP-3 tests and compared these with analytical predictions of pulse size, shape, and duration based on the theory of pressure wave propagation from underwater explosions. He found that recorded pulse characteristics agreed well enough with theory to enable the use of scaling laws to predict the strength of signals and the appropriate filters that should be applied.

Four penetrators of the ISP-4 design (Figure 4) were launched during the Tyro-84 cruise to the Nares Abyssal Plain. Two of them weighed 2360 kg and two weighed 2590 kg. All carried an improved version of EATS that was capable of transmitting more data than before. Each also carried an acoustic Doppler transmitter in the tail to allow an independent check on the data collected from EATS.

The first penetrator, a unit weighing 2590 kg, suffered a broken tail during launch and collected no useful data although the onboard EATS functioned properly. The second unit functioned properly and provided a full suite of data that agreed well with acoustic Doppler data. Data from the third and fourth units were only partially recovered because the ship drifted out of range of the transmitted signals.

ISP-4 contained the final version of EATS, and was thus capable of transmitting the most data. Besides conveying the impact velocity and depth of penetration, EATS also transmitted the number of data samples collected and the decelerations at 26 equally spaced times during the penetration phase of the flight. The total sequence of data is transmitted twice for

DIMENSIONS (mm)

Figure 4. General Configuration of ISP-4.

of penetration, EATS also transmitted the number of data samples collected and the decelerations at 26 equally spaced times during the penetration phase of the flight. The total sequence of data is transmitted twice for redundancy and also to maximize the opportunity of recording any data that might have been missed during the first sequence.

The last operational use of EATS occurred during the ACIS operation in 400 m of water near Toulon, France (Hickerson in Boisson, 1986). The system described above was employed on two ISP-4 penetrators, each weighing 2590 kg. Both data recording and transmission systems operated properly. However, one EATS began its operational sequence prematurely, and later, as the ship drifted out of range, a portion of the data transmission was lost. Figure 5 shows acceleration-time data recorded from the other unit. The velocity and depth vs. time as calculated from that data also appear in the figure. These measurements confirm the impact velocity and total depth of penetration that were also calculated by the EATS algorithms and transmitted with the deceleration data.

Two operational procedures became standard with the deployment of penetrators with EATS on board. As mentioned earlier, it is customary to calibrate the accelerometer sensor packages by simulating the penetration decelerations on the Sandia rocket sled track. Improved sensors might allow eliminating this step in the future. It is also commonplace to require shutting down all ship engines until all data are recovered to minimize the background noise created by the operation of this equipment. Unfortunately, this sometimes results in enough drift to carry the ship out of the range of the acoustic signals transmitted during the 30 to 40 min required to send all the data. There is currently no remedy for this problem, although larger explosive charges might help.

TOULON: TEST #2, SITE 02
ISP PENETRATOR, 2665 kg, 398 m OF WATER

Figure 5. Deceleration Data Recovered by EATS, and the Resulting Calculations of Velocity and Depth of Penetration.

3. MECHANICAL DESCRIPTION

3.1 General Description

EATS is composed of two major subassemblies - an electronics package containing the instrumentation, microprocessor control unit, and the fire set; and the detonator ring that forms part of the penetrator body and houses the explosive charges (Figures 2 and 3). A wiring harness joins the two electrically and transmits fire signals to the individual charges. The electronics package is contained within a sealed, high-strength steel housing. Waterproof, pressure-resistant connectors on the aft end of the housing mate with the wiring harness and allow internal communication during assembly, bench testing, and start of the launch sequence. The detonator ring, a heavy-walled aluminum component, also acts as a structural element of the penetrator and is used to join the body to the tail in ISP-4. During shipping, handling, and until launch, a blast shield termed a safety ring is placed around the detonators to safely contain any premature detonation of the charges.

Because a complete EATS is expensive, it is probably not cost-effective if large numbers of penetrator experiments are required. The electronics package costs about \$15,000 to build. The detonator ring assembly and wiring harness costs about the same. There is no way to reuse the hardware because the units are usually not recoverable after an experiment. James (1983) describes a recoverable instrument package that was fielded on ISP-2, a gun-fired penetrator, which might be adaptable to EATS if a similar experiment were required.

3.2 Electronics Package

The mechanical description of the Electronics Package for ISP-4 is described in the system level Sandia Drawing S48188, Issue A: Seabed Penetrator 40 Point Inst. Syst. and the subordinate drawings. The package consists of a housing and internal support assembly for the instrumentation

and electronics, and of the necessary mating and test connectors. The aft flange of the housing incorporates the mounting holes that allow for bolting the unit to a support inside the penetrator.

The electronics housing for EATS as deployed in ISP-4 (Figure 4) is a pressure-resistant vessel rated to about 100 MPa, or a depth of about 10,000 m. The housing, constructed of 4340 steel heat treated to a Rockwell C hardness of 40 to 43, is a simple cylinder terminated by top and bottom end plates. The outside diameter measures 152 mm, the wall thickness 10.2 mm, and the length 492 mm. Internal tie rods between the end plates hold the unit together and provide lateral support for the card cage and electronics. Standard O-ring seals are used as moisture barriers. To our knowledge, this design has never failed because of leakage.

Inside the housing a sturdy card cage, designed to withstand the forces of penetration, carries the electronics boards and batteries and is bolted to the bottom cap. The subassembly carrying the instrumentation and electronics is described in Sandia Drawing S455560, Issue A, Sea Penetrator Electronic Housing Assembly. Bolted to the aft end of the electronics card cage is the Darlington fire set and its power supply, described in drawings S48528 and S48440, respectively.

The top or aft-facing end plate mounts three Branter SEACON (registered trademark) connectors, a two-pin VSG-2-BCL, a three-pin VSG-3-BCL, and a four-pin VSG-4-BCL. The two-pin connector allows the operator to provide the "start" signal that begins operation of the unit. The other two connectors allow for performing test functions. The 40-pin interface connector, a specially built unit from SEACON, links the detonator ring to the fire set and is centrally mounted in this end plate. All connectors are waterproof assemblies, rated to 75 MPa, and mounted with O-ring seals to the end plate.

3.3 Detonator Ring

The ISP-4 detonator ring houses the 40 charges that are detonated to transmit the data collected by EATS. The ring also functions as a portion

of the penetrator body, and as such connects the forebody to the tail section. The 40 detonators are arrayed in two circumferential rings of equally spaced charges, each separated enough from its neighbors to prevent a sympathetic detonation when one is fired. The wiring harness is permanently mounted in the ring, and soldered connections are made to each detonator. The harness terminates in a 40-pin connector that mates with the output connector on the end plate of the electronics housing.

The detonator ring, a heavy-walled cylinder measuring 248 mm inside diameter by 324 mm outside diameter by 130 mm long, is described in Sandia Drawing S48435, Issue A: Detonator Ring. Recesses 20 mm in diameter by 27 mm deep in the outer surface of the ring accommodate two circumferential rows of 20 charges. A safe operating procedure, SOP 04000-8602, 1986, has been written to allow transport and operation of the assembled unit with explosives.

Charges for the detonator ring (Figure 6) are a Sandia design built by Space Data, Inc. of Salinas, CA. Each charge is built with a detonator containing 30 mg of B/CaCrO₄, 50 mg of PbN₆, and 100 mg of RDX that fires a pellet of HMX weighing 350 mg. Each charge contains a total of 530 mg of explosive. Charges are flush-mounted in recesses machined into the outer surface of the detonator ring, with electrical wiring fed to the charges through access ports in the ring.

Figure 6. Schematic Cross Section of the Explosive Charges (Dimensions in millimeters).

4. SYSTEM DESCRIPTION

A block diagram of EATS is shown in Figure 7. The microprocessor serves as a controller that can be programmed to acquire, store, and process data from as many as eight sensors and then encode the data to be telemetered into as many as 63 16-bit words. To date, only one of the eight input channels has been used with an accelerometer as the sensor. The EATS circuitry is similar to the Stored Data Acquisition System (SDACS) (Hauser and Ryerson, 1983) with the addition of the sequencer and fire circuitry. The sequencer receives a pulse from the microprocessor and causes the detonation of the proper explosive charge.

The microprocessor software is currently structured to fire several charges as the penetrator falls through the water toward the seabed. The data provided by the detonation of these charges are used aboard ship to estimate the terminal velocity of the penetrator. The software then turns its attention to acquiring samples of the deceleration of the penetrator as it penetrates and finally comes to rest in the sediment. These data are used by the microprocessor to compute penetration depth and the speed of the penetrator at sediment impact. These values, along with selected values of the deceleration, profile and the duration of the deceleration, are then encoded and transmitted by EATS.

Figure 7. Block Diagram of EATS.

5. PRINCIPAL SYSTEM BOARD DESCRIPTIONS

5.1 Central Processing Unit Board

The CPU board, the heart of the system, contains the central processing unit (CPU) and its control electronics. The CPU board (T75851) layout can be found in Figure 8 and the schematic in Figure 9. The board has five main sections: (1) the CPU, with memory-addressing and select terms, (2) the clock, (3) input/output (I/O) and interrupt control, (4) serial interface, and (5) system-fail detect circuitry. It is a general-purpose board allowing the user to change several parameters by changing jumpers (Table 1). For the ISP application, the jumpers elected are 1-3, 5-6, 7-9, 10-11, 13-14, 16-24, 17-25, 18-26, 19-23, 28-32, 36-37, and 39-43.

The CPU chip, U9, is an RCA 1806 operating at 2.4576 MHz. U10 is a latch to hold the high eight address lines from the CPU. The CPU has only eight pins to output 16 address lines. It does this by putting the high eight address lines out first with a strobe term, followed by the low eight address lines. U10 uses the high address strobe to latch the high eight address lines so they can be used with the low eight address lines to generate the total 16 lines. U11 is a counter used to generate a memory-select term (MSEL) that is true only when all 16 address lines are stable. This term, in conjunction with the memory read term (MRD) and memory write (MWR), is used to select memory.

The clock (U21) is a 2.4576-MHz, crystal-controlled oscillator. This is the clock frequency of the CPU. The clock also feeds a frequency divider, (U22) which generates the serial interface frequencies and the interrupt clock. U20 is a holding register and U19 is an eight-channel multiplexer. Under software control these chips allow changing the bit rate of the serial interface. U13 is a divide-by-three integrated circuit used to generate the real-time clock for software timing. The input frequency to this divider is jumper-selectable to allow different real-time clock frequencies.

Figure 8. The CPU Board Layout.

TABLE 1

CPU Board (T75851) Jumpers

One of the following connections must be made for each pad group.

Pad Group	Connect Pads	Function
1- 3	1 to 3	not functional (1 and 3 must be connected)
4- 6	4 to 6 5 to 6	enables automatic power fail detect and reset disables automatic power fail detect and reset
7- 9	7 to 8 7 to 9	connects logic level serial input connects RS-232 serial input
10-12	10 to 11 10 to 12	puts serial-received bit rate select under software control sets serial-received bit rate to 75 bits/s.
13-15	13 to 14 13 to 15	puts serial-transmitted bit rate select under software control set serial-transmitted bit rate to 75 bits/s.
16,20,24	16 to 20 16 to 24	disables real-time clock interrupt enables real-time clock interrupt
17,21,25	17 to 21 17 to 25	disables serial-received data interrupt enables serial-received data interrupt
18,22,26	18 to 22 18 to 26	disables serial-transmitted data interrupt enables serial-transmitted data interrupt
19,23,27	19 to 23 19 to 27	disables analog digitizer interrupt enables analog digitizer interrupt
28-35	28 to 32 & 30 to 34 29 to 33 & 31 to 35	allows a 2732 PROM to be used on CPU board allows a 2716 PROM to be used on CPU board
36-38	36 to 37 36 to 38	real-time clock signal generated on CPU board real-time clock generated external to CPU
39-46	39 to 43 40 to 44 41 to 45 42 to 46	sets real-time clock interrupt to 800 Hz sets real-time clock interrupt to 400 Hz sets real-time clock interrupt to 200 Hz sets real-time clock interrupt to 100 Hz

U8 is a decoder used to generate device select terms for enabling I/O devices. These terms, along with the input select (INS) and the output select (OUTS) terms, decode the INP and OUT software instructions to transfer data to and from the I/O devices. Chips U14, U15, U16, and U17 are used to generate I/O device interrupts. Interrupts from different devices can be selectively enabled or disabled by jumpers 16 through 27.

U25 is an Intersil 6402 universal asynchronous receiver/transmitter (UART). The UART is a parallel-to-serial and serial-to-parallel converter used to input and output serial data to the CPU. It also adds communication synchronizing bits for serial transmission and checks and removes these bits during serial receiving. In this system the UART is used to receive system commands and to output recorded data during setup and testing. U23 is an amplifier used to generate RS-232 output voltage levels from the UART-generated serial data stream.

U6 and U7, in conjunction with the Q-bit line, are used to generate an automatic reset on system fail. ISP does not use this option, and the Q-bit is used on the sequencer board to toggle the explosive charge fire sequencer.

U27 is a chip location for a 27C16 or 27C32 programmable read only memory (PROM). This application does not use U27.

5.2 Memory Board

The memory board holds both the programmable read-only memory (PROM) for program storage and the random access read/write memory (RAM) for data storage. Figure 10 gives the memory board layout, and Figure 11 presents the schematic. The board is designed to use 27C16 or 27C32 PROMs giving 8 kbytes or 16 kbytes of program storage, respectively. In this application 27C16 PROMs were used.

The memory board also contains 12 Harris 6516 or Hitachi 6116 CMOS RAM chips, U5 through U16. Each chip has a capacity of 2 kbytes of memory for a

Figure 10. The Memory Board Layout.

Figure 11. The Memory Board Schematic.

TABLE 2
Memory Board (75874) Jumpers

Pad Group	Connect Pads	Function
1-23	1 to 3 & 2 to 5 & 6 to 8 & 9 to 10 & 12 to 13 & 15 to 16 & 18 to 19 & 21 to 22	allows 2716 or 27C16 PROMs to be used (27C16s required because of power constraints)
or	2 to 3 & 4 to 5 & 7 to 8 & 10 to 11 & 13 to 14 & 16 to 17 & 19 to 20 & 21 to 23	allows 27C32 PROMs to be used

total of 24 kbytes of memory for data storage. The memory board has tri-state buffering of all data and address lines to prevent loading of the CPU board.

5.3 Analog and Sequencer Board

The analog and sequencer board contains the analog signal processing for two analog channels, the multiplexer or switch to feed one of the two channels to the digitizer, the digitizer or analog-to-digital (A/D) converter, and the sequencer for firing the acoustic detonators. It also contains the power supply for the system. Figure 12 gives the layout of the board; Figure 13 is the schematic.

The digitizer (U1) is a National ADC0808 A/D converter. The ADC0808 contains an 8-channel multiplexer followed by an 8-bit A/D converter. It has a total conversion time of 119 μ s/sample; that is, 119 μ s to digitize one channel of data. Two of the eight analog channels have onboard signal-conditioning circuitry.

Figure 12. The Analog and Sequencer Board Layout.

The analog front end of each channel is a National LH0036 instrumentation amplifier (U3) and (U18). These amplifiers provide isolation and an adjustable gain of 1 to 1000 by selection of values of resistors R2 and R105. The LH0036 has a differential input with an isolation of 1 m Ω to ground per input and 2 m Ω between inputs.

Following the input amplifier is a four-pole, antialiasing, low-pass filter. The filter provides an attenuation of 24 dB/octave above the cutoff frequency. Filtering is done in two stages. The first stages are U4 and U19; the second stages are one-half each of U5 and U20. Each stage is two-pole, giving an attenuation of 12 dB/octave above the cutoff frequency. The filter parameters can be set by using the equations in Figure 14 to solve for component values for each stage.

Following the filter is a buffer amplifier for each channel. These amplifiers (the second half of U5 and U20) are used to adjust the channel gain and to give DC offset to put the signal in the 0 to 5-V range of the ADC0808. Also included with these amplifiers is the over-under voltage protection. The LM103 zener diode and the 5A12 diode limit the input of the ADC0808 to a 0 to 5-V level to prevent the ADC from saturating and giving channel crosstalk.

Another section of this board is the circuitry to control and fire the explosive charges. This circuitry consists of (1) a safe/arm relay, (2) a dual one-shot to control pulse widths, (3) a counter to keep track of the charge being fired, and (4) multiplexers to select the correct charge.

Under software control, U17 controls the safe/arm relay (K1). When K1 is off, the explosive acoustic charges cannot be fired.

The firing of an explosive acoustic charge is initiated by the software setting the CPU Q-bit. Figure 15 is a timing diagram of this sequence. On the trailing edge of the Q-bit, a 10-ms fire pulse signal is generated by one of the one-shots in U7 and routed to the correct charge by multiplexers U6, U9, U10, U11, and U12. The trailing edge of the fire pulse is used to trigger the second one-shot in U7 for 1 ms. The trailing edge of this pulse

$$\text{DC Gain} = H_0 = 1 + \frac{R_4}{R_3}$$

$$\text{Cutoff Frequency} = f_0 = \frac{1}{2\pi} \left(\frac{1}{C_1 C_2 R_1 R_2} \right)^{\frac{1}{2}}$$

$$\text{Damping} = d = \left(\frac{C_2 R_2}{C_1 R_1} \right) \left(1 + \frac{R_1}{R_2} - \frac{R_4 C_1 R_1}{R_3 C_2 R_2} \right)$$

where critical damping = $\sqrt{2}$

For minimum output offset, let $R_4 = (R_1 + R_2) H_0$

Possible Simplifying Assumptions

1. Unity Gain $H_0 = 1$ when R_3 removed = infinity
2. Equal Component $R_1 = R_2$ and $C_1 = C_2$

Figure 14. Equations for Filter Parameters.

FIRE PULSE TIMING

Figure 15. Fire Pulse Timing Diagram.

is used to increment counter (U8), which controls the multiplexers that select the correct charge.

When the system is turned on, U8 is reset so that it points to the first charge. After each fire pulse, the system increments as described above to the next charge. The sequencer can fire 64 separate charges.

Also included in the analog-sequencer board is the power supply for the entire system. U13 is a three-terminal regulator to generate +10-V for powering the accelerometer. U14, a three-terminal regulator, generates +15 V for the analog switches (U6 and U9 through U12) and powers the relay (K1). U16 is a regulator to provide +5 V at about 50 mA for all of the logic circuits. U15, a switching regulator, generates -9.3 V at about 20 mA. This supply, in conjunction with +9.3 V off diode CR3, is used to power the analog circuits and the serial interface on the CPU board.

6. DESCRIPTION OF THE SOFTWARE

The software consists of seven main sections and is written in assembly language to gain the high speed required for data acquisition. The sections are initialization, data gathering, integration, encoding, telemetering, command processing, and interrupt service routine. Figure 16 is the main system flow chart showing these sections. Figures 17 through 22 are flowcharts of the critical sections of the software.

The initialization routine is entered when the system is powered up. This routine sets up the I/O hardware, the CPU registers, and the variables in RAM. At the completion of the initialization routine, the software goes into the data-gathering routine.

Figure 17 flowcharts the data acquisition routine. On entering the data gathering routine, the system waits for a zero bias command that enters the level of no acceleration. Next, a threshold command is entered to set the level at which the system starts recording data. Third, a verification delay command is entered to set the time at which the verification charge is fired after the arm command. When a Cal or Flash command is given, the system exercises the sequencer and fires all charges from a stored table of times. These commands are for system checkout before installation. When an "Arm" command is entered, the system waits for the verification delay to expire and fires the verification charge. The system then waits for saltwater switch closure and fires Charges 2, 3, and 4 at predetermined times. The software waits 1 s and starts storing acceleration data in the 29.44 s circular memory. When the threshold exceeds 24.44 s, more data are stored, keeping a 5-s precursor.

Figure 18 flowcharts the integration routine. After data gathering routine and memory are full, the intergration routine is entered. The software finds the first sample to integrate, the last sample to integrate, and the number of samples to integrate. The first and second sums are then

Figure 16. Main System Software Flowchart.

Figure 17. Data Acquisition Flowchart.

Figure 18. Integration Routine Flowchart.

Figure 19. ISP Encoding Routine Flowchart.

Figure 20. Telemetering Routine Flowchart.

Figure 21. Command Processing Routine Flowchart.

Figure 22. Interrupt Service Routine Flowchart.

computed to determine terminal velocity and depth of penetration. The maximum data sample is also found.

The software then enters the ISP encoding routine (Figure 19), which selects the data to be telemetered. The depth and speed are encoded, followed by the number of samples integrated and the deceleration data. Next, the detonation times in the table are adjusted according to the new data.

The telemetering routine shown in Figure 20 is then entered. The system waits for a clock interrupt and then starts a timer and triggers the sequencer and fires the charges according to the new times in the table until all charges are fired.

The sixth software routine is the command processing routine (Figure 21). This routine is started whenever a valid command is received over the RS-232 serial input line. The interrupt service routine determines which command was input and starts the section of code in the command processing routine which handles that command. The flowchart indicates commands that are valid and recognizable by the system.

The last major software routine is the interrupt service routine (Figure 22). This routine handles software interrupts from the real-time clock, the RS-232 serial input, and the RS-232 output. It decodes commands input on the RS-232 serial interface and starts the section of the command processing routine corresponding to the command input.

7. SUMMARY AND CONCLUSIONS

The explosive acoustic telemetry system, EATS, has now been fielded on four separate occasions in penetrators launched in water depths ranging from 22 m to 5800 m. In all instances the units functioned properly or with only minimal problems. In its latest version, EATS is capable of collecting and transmitting data giving the impact velocity of the penetrator, the depth of penetration, and 26 data points on the deceleration curve. For the sake of redundancy these data are transmitted twice. The redundant data could be replaced with information from other sensors or other data in memory by modifying the software.

The advantages of EATS are the reliability of the system in deep water and the strength of the transmitted signal. Countering these advantages is the observation that ship engines must be shut down before the acoustic signals can be received, sometimes resulting in the loss of data if the ship drifts too far off-station. Further, EATS is expensive, costing about \$30,000 for a complete system that is usually not recoverable after the experiment.

Drawings and electrical schematics are available for all components. Considerable documentation also exists for the basic principles of operation and the early development of the hardware.

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