Damage Dosimeter: A Portable Battery Powered Data Acquisition Computer

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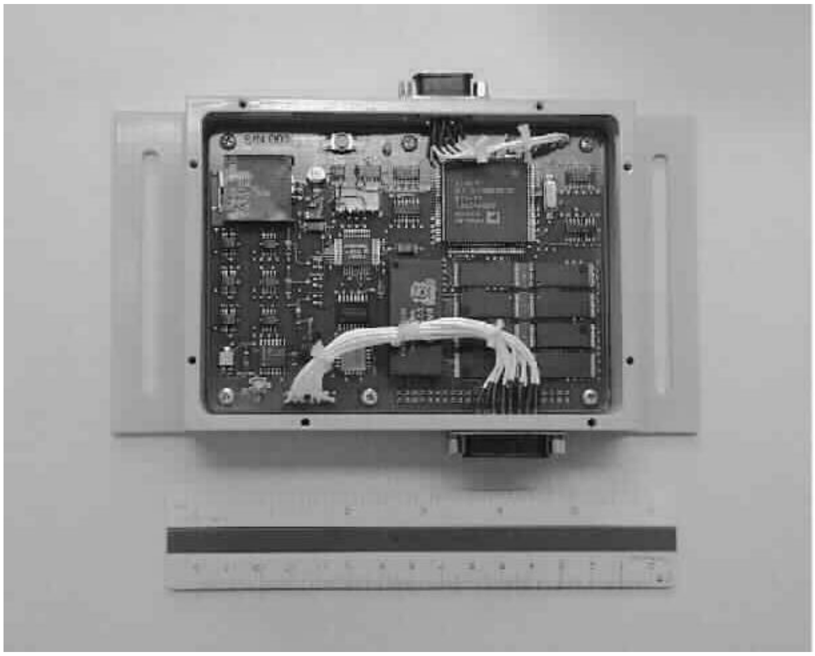
Abstract

The Damage Dosimeter has been designed to fill a void in commercially available data recorders. The United States Air Force often has the need to measure structural strains and temperatures on in-service aircraft in order to diagnose difficult-to-analyze structural conditions, such as high cycle fatigue. To perform these functions a rugged, small, and lightweight data acquisition unit called the Damage Dosimeter has been constructed. Running off of battery power in an autonomous fashion the Damage Dosimeter measures 3 channels of strain at sample rates as high as 15 kilo-samples per second and a single channel of temperature. The Damage Dosimeter merges the functionality of both the analog signal conditioning and a digital single board computer on a single 3.5 inch by 5 inch card. The entire unit (sans battery) weighs less than 1.5 lb. and fits in the palm of your hand. This paper will discuss the motivation and requirements for the Damage Dosimeter, along with an overview of the design and construction. Finally, the software, operational modes, and sample data will be presented.



OVERVIEW

The United States Air Force (USAF) has funded the design, construction, and testing of the Damage Dosimeter as part of the Durability Patch Program. The Durability Patch Program's goal is to develop repairs for secondary structure[1] that restore structural integrity and increase the structure's damping in the repair region. Increased damping leads to reduced resonant response and a repair that will outlive the aircraft, as opposed to a repair that will need replacement in a thousand flight hours. In order to design a repair with effective damping properties, the in-service structural strains and temperatures must be known, since damping material properties are a function of both frequency and temperature. The Damage Dosimeter allows an engineer to easily instrument an in-service aircraft to obtain the structural characteristics necessary to properly select damping materials, and design a repair with optimum effectiveness. An overview of the Durability Patch Design Process is shown in Figure 1.

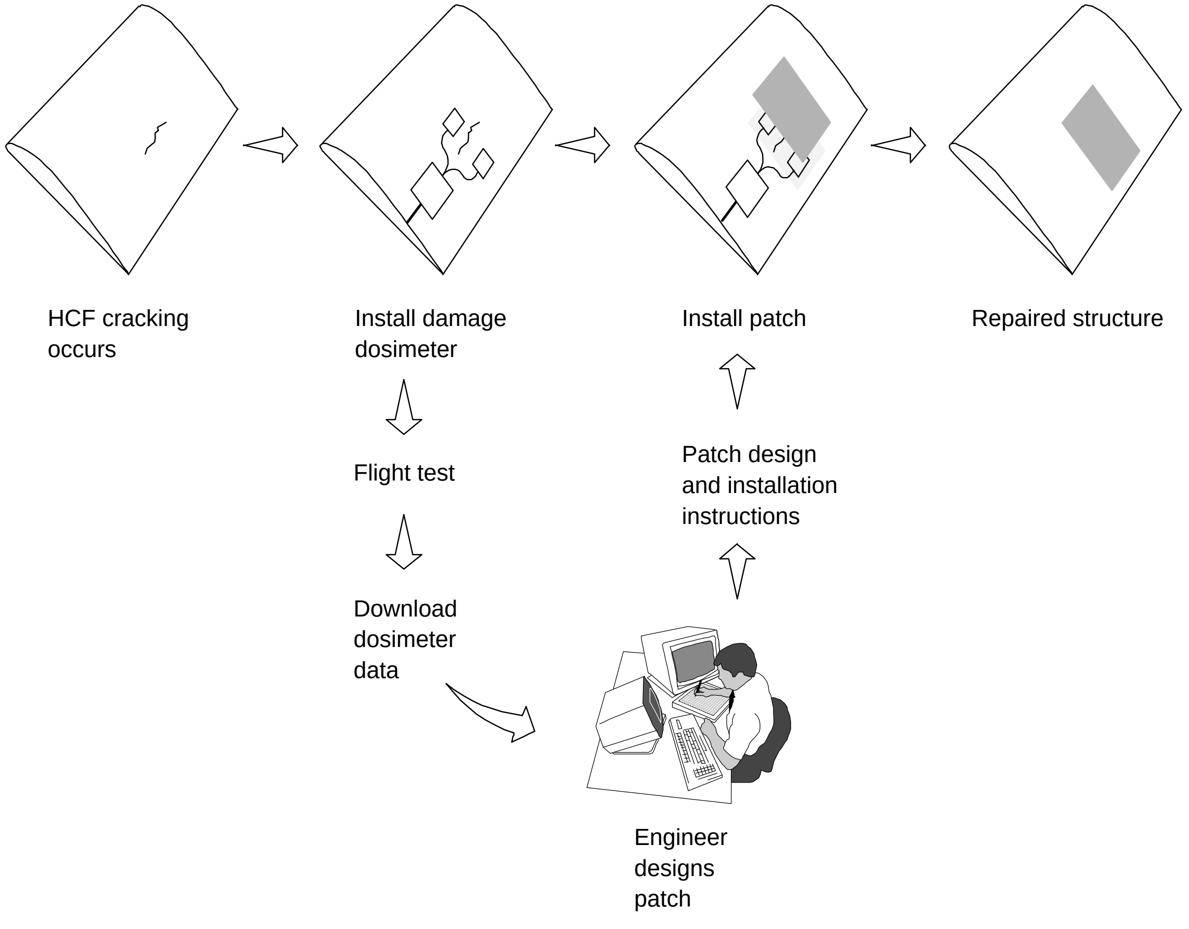


Figure 1: Durability Patch Design Process

The process in Figure 1 shows the steps in an idealized procedure to design and install a high-cycle fatigue repair. The Damage Dosimeter is necessary to gather the design information

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[1] Secondary structure is not safety of flight critical. Typically this sort of structure does not carry very high loads, and is often minimum gage.

(structural strain and temperature) for the repair, and can also be used to check the effectiveness of the repair after it is installed. In order to minimize the impact on an aircraft's normal operations, the Damage Dosimeter is a stand-alone device that does not require aircraft power or cooling. This greatly reduces the amount and severity of modifications to the aircraft in order to use a Damage Dosimeter, and greatly reduces the amount of effort and calendar time required to fly additional instrumentation on a military aircraft. In addition to being battery powered, the Damage Dosimeter operates autonomously again, a measure designed to reduce interference with the aircraft and its crew once the Damage Dosimeter is installed. Once installed the Damage Dosimeter checks the sensors at a preprogrammed interval to determine if data acquisition is necessary. The raw data are low frequency structural temperature (approximately 1Hz), and high frequency (approximately 10kHz) structural strains. The processed data are strain time histories of RMS values in pre-defined 1/3-octave bands. This is a valid approach for high cycle fatigue situations where the structural response is typically narrowband and random. Data gathering time is limited by the quantity of memory. The stand-by time is limited by battery capacity. Data is stored in non-volatile memory; no data is lost if the battery is depleted. A PC then downloads the data gathered at a convenient time. This data is given to the Durability Patch design engineer for use in selecting the best visco-elastic damping material properties, and for designing the optimum overall repair [1].

Optionally, the Damage Dosimeter can be left on the aircraft, or re-installed after the aircraft has been repaired to verify that the repair does achieve its objectives. The repair effectiveness can be demonstrated by either comparing the before and after strain magnitudes in certain 1/3 octave bands, or by computing structural damping from the raw time histories and comparing the before and after structural damping properties.

At the outset of the Durability Patch program a survey of existing commercial data recorders and loggers [5] did not yield a Commercial Off The Shelf (COTS) product that could:

- Record three channels of strain data from 5 kilo-samples per second (ksps) to 15 ksps.
- Meet our weight and size goals of 1.5 lb. and 3 inches by 5 inches by 1 inch for the Damage Dosimeter (same goals for the battery).
- Operate on battery power for at least a week.
- Perform complicated data analysis. Multiple Discrete Fourier Transforms (DFT) are performed for each data processing cycle. A relatively fast DSP is required to get the required performance.
- Provide the necessary flexibility (programmability) for differing applications.

The Durability Patch Program set out to develop its own data acquisition computer, and nicknamed it the Damage Dosimeter, since one of its outputs is a measure of cumulative structural damage.

The Damage Dosimeter monitors three strain gages and a temperature sensor. The strain gages are configured in an Anderson loop with constant current excitation. These four channels of analog data are converted to digital data. The digital data are then processed by a digital signal processor (DSP) and stored in flash memory. Data download and program upload is accomplished via an RS-232 connection to a PC. A block diagram of the Damage Dosimeter functionality is shown in Figure 2.

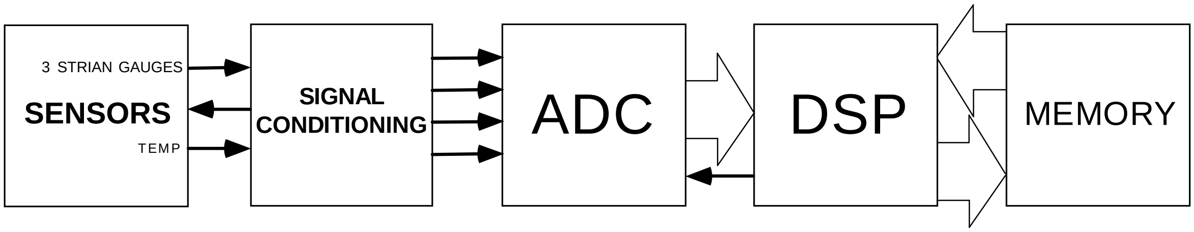

Figure 2: Damage Dosimeter Functional Schematic

REQUIREMENTS

In addition to the usual technical requirements such as sample rates and passband frequencies, the dosimeter was designed with an additional set of user-requirements. These requirements do not directly improve the performance of the dosimeter. Rather, they help insure that the dosimeter will actually be used in the future by making the dosimeter as easy, and efficient as possible to use. The biggest obstacle in instrumenting an aircraft is making modifications to the aircraft electronics, even to draw power. Requiring that the dosimeter run off of battery power eliminates the concerns associated with integrating new electronics on an existing aircraft. Additional requirements on dosimeter and battery size and weight help insure that the dosimeter can be used on as many different aircraft as possible. Lastly, requiring that the dosimeter operate with up to 50 feet of strain gage lead wire length, and 100 feet of battery power cable offers the end user plenty of flexibility in finding suitable mounting locations for both the dosimeter and battery.

Operational requirements are as follows; the Damage Dosimeter must gather strain data from three strain gages, this data must have 5 μ-strain resolution, sampled at 10kHz, over the frequency range of 50Hz to 5kHz. The temperature data must be +/- 2 ^{o}C, sampled at 1Hz. The Damage Dosimeter data shall be time stamped (Date, Hour, Minute, Second). The Damage Dosimeter data shall be a “once a second” representation of the frequency, amplitude, temperature and time stamp of the instrumented area. The Damage Dosimeter shall store sample time history data for peak strain for each channel, peak RMS strain for each channel and minimum temperature in a Time History format (storage of all raw data for that sample). The Damage Dosimeter shall operate in the *industrial* temperature range (-40^{o}C to +85^{o}C). The Damage Dosimeter shall be able to operate in a standby mode for ten days, and be able to collect ten hours worth of data anywhere in those ten days. The Damage Dosimeter data shall be capable of communicating with a laptop PC, including data download. The operational software (embedded) shall be written in the C-language, and compiled on and uploaded from a laptop PC.

DESIGN

DATA ACQUISITION

The Signal conditioning utilizes the Anderson Constant Current Loop [2] conditioning, shown in Figure 3, to interface three strain gages to the analog to digital converter (ADC). The temperature sensor current proportional output is measured across a series resister.

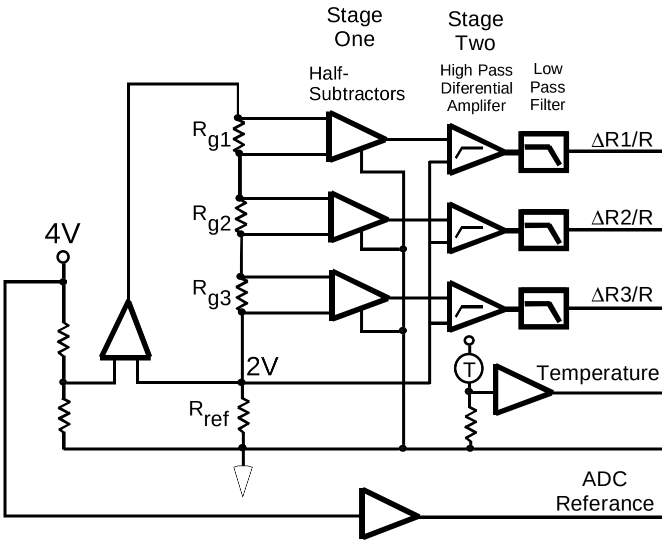

Figure 3: Anderson Constant Current Loop Block Diagram

Strain Measurements

The Damage Dosimeter strain gages are resistive strain gages. The change in resistance in the gages is proportional to the physical change of the length of the gage. The gage is intimately bonded to the aircraft structure such that the change in the length of the gage is the change in the material. The strain is equal to:

$$\text{Strain} = (\Delta R/R_g)/GF$$

Where ΔR is the change in the gage, R_g is the nominal resistance of the gage, and GF is the gage factor (provided by the manufacture). It is the $\Delta R/R_g$ change in resistance that the Damage Dosimeter is to measure.

The three strain gages and a reference resistor are connected in series with a current source (see Figure 3). The current in the loop is calibrated to give a voltage drop across the 350Ω reference resistor of 2 volts, this is equal to ½ the ADC reference voltage. The voltage drop across each gage passes though an RFI filter to two amplifier stages [3]. The first stage accomplishes active subtraction by replicating the voltage drop across the strain gage at a point where it can be observed in series opposition across the reference resistor. The second stage amplifies the difference between the gage voltage and the reference voltage with an amplifier having a high pass response. The reference voltage of the second stage is [(1/2)ADC_{ref} – the gage DC offset]. The scale is set by the gain in the second stage. The gain of the second stage is adjustable by a single component change (feedback resistor). The Damage Dosimeter at present has a full-scale measurement of +/- 3000 μ-strains. The Anderson loop was used for its low power requirement and the measurement's independence upon lead wire length. The installation of the Damage Dosimeter will be different with each application. Thus, usage is simplified if the lead wire length does not affect measurement sensitivity.

Temperature Measurement

The temperature sensor is a two-terminal integrated circuit temperature transducer that produces an output current proportional to absolute temperature. For supply voltages between +4 V and +30 V the device acts as a high impedance, constant current regulator passing 1 $mA/^oK$ [4]. One terminal of the temperature sensor is connected to the +12V supply. The other terminal is connected to analog common through a 1KΩ series resistor. The voltage drop across the 1KΩ resistor is amplified with an instrumentation amplifier with a gain of ten. This is done to scale the measurement and to produce buffered input for the ADC.

Digital Conversion

A single ADC converts the outputs of the signal conditioning to 12-bit data. The multiplexing and sample rate of the ADC is controllable by the DSP. The inputs to the ADC are low pass filtered with an anti-aliasing single pole passive filter. The present design's –3db point is set to 5kHz. The filter is a simple RC network, so making a single component change can modify the corner frequency. The reference for the ADC is generated by the same voltage reference that is used to regulate the loop current. This is done to achieve a high pass zero corrected ratiometric measurement and to automatically adjust average strain gage output to mid-scale of the ADC.

The voltage of interest is: $V_0 = V_g - V_{ref}$

$$V_0 = I\,(\Delta R + R_g) - I\,(R_{ref})$$

When the reference resistor is equal to the nominal gage resistance:

$$V_0 = I\,(\Delta R)$$

The output of the ADC is the ratio of the voltage at the input (V_0) divided by the reference voltage for the ADC (V_{REF}):

$$DATA = V_0/V_{ADC\text{-}ref}$$

Since the same reference voltage source is used for the ADC reference and to determine the set point for the current loop:

$$\text{DATA} = I\,(\Delta R + R_g) - I(R_{ref})/I\,(R_{ADC\text{-}ref})$$

Yielding as the data point:

$$\text{DATA} = \Delta R/R_g$$

DATA PROCESSING

All data processing functions are performed on the Analog Devices ADSP-2181 chip. The ADSP-2181 is a fixed-point processor that runs at 33Mhz and consumes a minimal amount of power for a DSP. The DSP contains 16k words of program memory on board the chip, allowing the processor to boot its program from flash memory and load the program, in its entirety, into RAM.

The data processing portions of the dosimeter programs are written in the C-language. Analog Devices sells a development kit that includes a C compiler, assembler, linker, and prom-splitter. With these tools, the dosimeter programs have been developed on an Intel PC. Only a minimal effort was made to keep the dosimeter programs under the 16k word size limit so that program paging and memory allocation could be avoided. This effort involved using a shorter length DFT and manually performing the decimation in time operation. This effort saved 2048 words of array space by reusing the complex portion (which is all zeros) of the input to the high speed DFT subroutines supplied by Analog Devices.

The remaining operations are a mixture of mostly integer and some floating point[2]. The fundamental operation is the computation of the Power Spectral Density (PSD), also known as the signal Autospectrum. The PSD is by definition positive and real valued:

$$\tilde{G}_{xx}(f_x) = \frac{2}{N\Delta t}|X(f_k)|^2, k = 0,1,2,\ldots\frac{N}{2}$$

Where

$$X[k] = \sum_{n=0}^{n=N-1} x[n]e^{-j(2\pi/N)kn}, k = 0,1,2,\ldots N-1$$

Is the definition of the Discrete Fourier Transform (DFT). Once the PSD has been calculated, the 1/3 octave band RMS values can be calculated with a simple integration scheme. The dosimeter uses the trapezoidal rule for this purpose.

The ADSP-2181 has 16k words of data RAM (in addition to the program RAM) allowing all calculations to be performed in RAM. At the conclusion of the data processing cycle, the output is written to non-volatile flash memory.

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[2] Floating point operations are performed in software.

SOFTWARE

The Damage Dosimeter's operational software program was written in the C-language to allow the code to be easily maintained. Although the software that is embedded in the Damage Dosimeter is C compileable the low level device drivers are written in assembly code for the DSP. The device drivers are C callable. The device drivers were written in assembly language for two reasons. First, they are more efficient and second they can be reused in many different configurations mitigating the need to be maintained. The embedded code was designed to be easily modified since the use of the Damage Dosimeter will change slightly from application to application. Each function of the Damage Dosimeter was modularized and program variables (such as sample rate, etc) are visible at the top-level program. Modification of the Damage Dosimeter's embedded code is accomplished by integrating new values for the program variables. Integration of all modules is accomplished by compiling an executable program that is uploaded to the Damage Dosimeter via a serial port. The Damage Dosimeter's operational software resides in flash memory so that it is modifiable in the circuit.

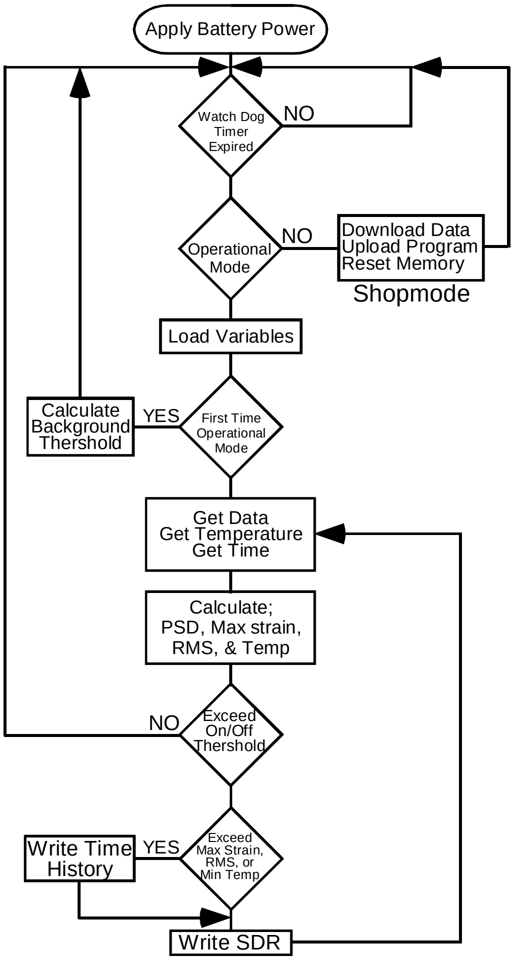

FIGURE 4: Damage Dosimeter Software Flow Diagram

POWER SUPPLY – BATTERY

The Damage Dosimeter requires +/- 12VDC. The analog front end uses +/- 12V and the digital back end runs on +5V. The +5V is derived from the +12V by a switching regulator on the Damage Dosimeter board. Efficient operation, or low power draw, was a primary consideration during the design of the dosimeter. As a result power consumption during data gathering operations is less then two watts. In spite of the low power draw the need to operate the dosimeter in temperatures as low as -40^{o}C drives the need for specialized batteries. Lithium battery chemistries offer the highest energy densities in primary (non-rechargeable) cells. After running several cold temperature tests the Li-MnO_2 battery chemistry was chosen. After further testing, the Duracell D2/3A cells were chosen, primarily for their ability to withstand the large (2 ampere) in-rush currents. The batteries are not rechargeable but are readily available and inexpensive (about 3-4 dollars per cell). 15 cells are required to power the dosimeter through a typical mission. After each mission, the positive side battery pack (10 cells) must be replaced. The negative side pack (5 cells) can last up to 7 missions. Figure 5 shows both the negative (in the rear) and the positive (in the middle) packs. In the forefront is a single Duracell cell. If the missions are shorter in duration, or moderate temperatures are experienced, the battery could last significantly longer. The battery is housed in a COTS die-cast aluminum box lined with polyethylene foam for vibration isolation.

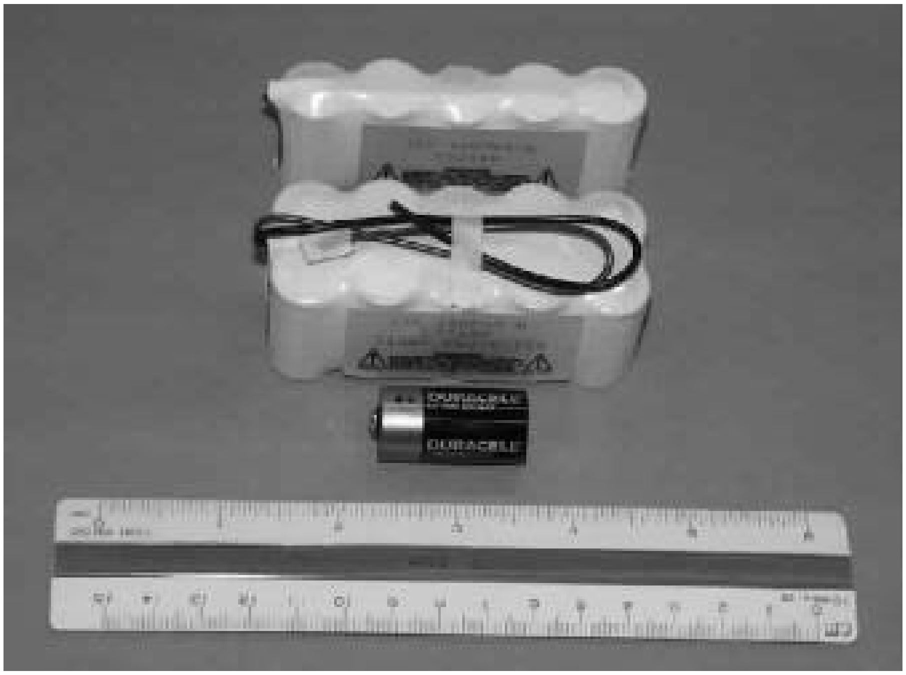

Figure 5: Damage Dosimeter Battery Cells

DAMAGE DOSIMETER OPERATION

The Damage Dosimeter has two modes of operation: acquisition mode and shop mode. The Damage Dosimeter does not need disassembly, or adjustment to switch between modes. Simply plugging the supplied[3] serial communications cable into the Damage Dosimeter will force the Damage Dosimeter into shop mode during the next power-up cycle. Acquisition mode refers to the mode in which the Damage Dosimeter gathers, processes, and stores strain and temperature data. Shop mode refers to the mode in which a laptop computer can communicate with the Damage Dosimeter, either downloading data, or uploading new programs. A simple program, which runs on DOS, Windows-95, or Windows-NT, provides the user interface to the Damage Dosimeter when in shop mode.

Although the Damage Dosimeter is programmable, we will describe in some detail how the Damage Dosimeter programs function in their current incarnation. The previous section, discussing the Damage Dosimeter software, shows what portions of the software are easy to modify and what parts should be left alone.

Acquisition Mode

When power is applied, and no serial cable is connected, the Damage Dosimeter defaults to the data acquisition mode and waits for the watchdog timer (WDT) to expire. The first power on cycle after the Damage Dosimeter has been reset performs a self-calibration. The Damage Dosimeter collects 20 seconds worth of data (with the gages inactive), and uses that data to calculate a background noise value[4]. The background value is then multiplied by a programmable variable, and used as the background threshold for the algorithm that decides if data collection is warranted (power on/power off). The calibration cycle then refreshes the WDT and turns the Damage Dosimeter off. When the WDT next expires (the WDT length is a programmable variable) the Damage Dosimeter boots, gathers one set of data, enough for one SDR, and uses the background threshold and the new data to decide if the gages are active. If the output of the gages does not exceed the background threshold the Damage Dosimeter refreshes the WDT and turns itself off. If the new data exceeds the background threshold then the Damage Dosimeter starts data collection. The new data is processed into the SDR format and stored in flash memory in a location pointed to by the memory manager. The Damage Dosimeter continues to collect data until either the memory is full or the gage activity level falls below the background threshold for ten[5] consecutive seconds. The ten consecutive seconds is used so that a brief period of gage inactivity does not cause the Damage Dosimeter to shutdown. If the Damage Dosimeter turns itself off it will then revert back to powering on every WDT period and checking the gages for activity. When the memory is full the Damage Dosimeter will turn itself off. It will then turn itself on every WDT period determine the memory is full and shut itself off. The Damage Dosimeter will not overwrite previously stored data.

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[3] The serial cable is special. Pins 5 & 9 on the Damage Dosimeter end of the cable are connected together.

[4] The background noise value is the average of the root mean squares of each data set.

[5] This value is programmable.

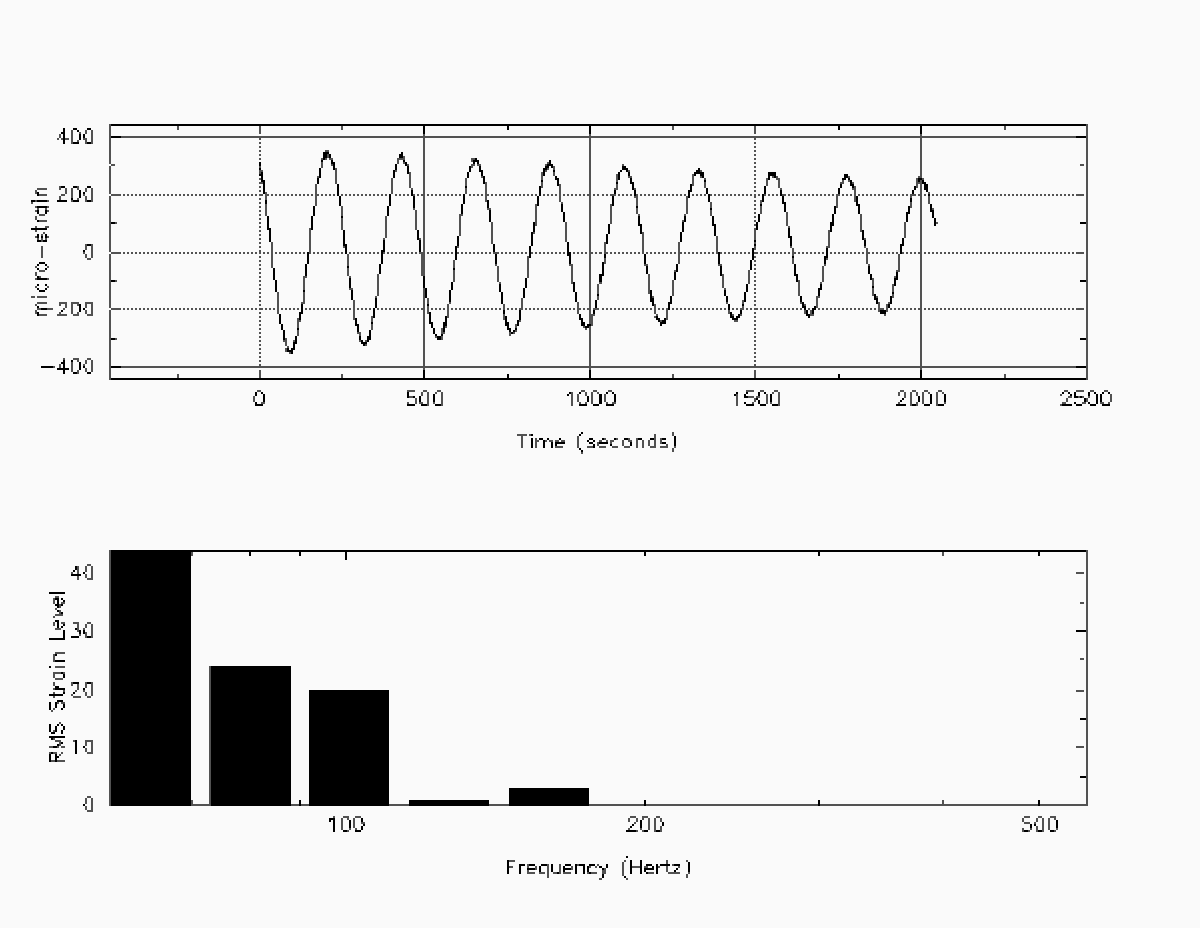

Figure 6: Sample Dosimeter Raw, and Processed Data

Figure 6 shows a sample of low frequency data acquired with the dosimeter. The upper plot is the raw time series of a single strain gage. The lower plot is the 1/3 octave band RMS strain levels for the time history shown.

Shop Mode

When power is applied, the Damage Dosimeter boots, and checks the status of the RS-232 connector. If the supplied serial cable is plugged into the Damage Dosimeter, then the Damage Dosimeter enters shop mode. The program *Floader*, a DOS program that will run on DOS, Windows-95, and Windows-NT, uses a simple menu-driven user interface to perform the following functions:

- Download processed and/or raw data from the Damage Dosimeters non-volatile RAM. The user has the choice of downloading just the processed data, and/or downloading raw time histories that are stored in a pre-defined location in memory.
- Download arbitrary (user specified) portions of memory in binary or hexadecimal format.
- Download data from the Damage Dosimeter's non-volatile SRAM.

- Clear the Damage Dosimeter’s memory.
- Modify the time of day, or date in the Damage Dosimeter’s real time clock.
- Upload new programs to memory to modify the Damage Dosimeter’s behavior.

Once the user has performed the necessary functions with the *Floader* program, the program is exited, and the serial cable is disconnected. The next time the Damage Dosimeter boots itself it will go into acquisition mode.

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REFERENCES

[1] Rogers, L. C. and Searle I. R., “Durability Patch: repair and life extension of high cycle fatigue damage on secondary structure of aging aircraft” DOD/FAA/NASA Conference on Aging Aircraft, July 8-10 1997, Ogden UT

[2] Anderson, K. F., “Practical Applications of Current Loop Signal Conditioning”, Technical Memorandum: NASA-TM-4636, Jan 1995, NASA Dryden Flight Research Facility, Edwards CA.

[3] Wong, J., “A Collection of Amp Applications”, Application Note AN-106, Analog Devices, Norwood, Ma

[4] Klonowski, P., “Use of the AD590 Temperature Transducer in a Remote Sensing Application”, Application Note AN-273, Analog Devices, Norwood, MA.

[5] Schreier, Paul, Editor, “For data collection at rugged or remote sites, loggers still rule”, Cover Story, Personal Engineering & Instrumentation News, August 1997, Vol 14, No 8.

[6] Dallas Semiconductor, “Watchdog Timekeeper” Application Note 66, Dallas Semiconductor, Dallas, TX.