A QUICK LOOK AT FLIGHT DATA FROM A DIGITAL DAMAGE DOSIMETER

David Banaszak and Dansen Brown Air Force Research Laboratory
Dr. Angela Trego, P.E., The Boeing Company.

Biography

David Banaszak received a Bachelor of Science (BS) in Electrical Engineering from the University of Wisconsin and a Master of Science (MS) in Applied Statistics from Wright State University. Dave works for the Air Vehicles Directorate of the Air Force Research Laboratory (AFRL/VA) and does acoustic, vibration and loads measurements for numerous laboratory and field test programs. Dave is a member of the American Institute of Aeronautics and Astronautics, American Statistical Association and Vehicular Instrumentation/Transducer Subcommittee of the Range Commander's Council Telemetry Group. He is President of the Greater Ohio Chapter of the Institute of Environmental Sciences and Technology (IEST).

Angela Trego, Ph.D., P.E., is a Senior Specialist Engineer at Boeing Phantom Works in the Structures Technology group. Responsibilities include structural health monitoring, fiber optic sensor technology, corrosion assessment of aging aircraft structures and general dynamic analysis of structures. She is the author of 15 publications ranging from the development of passive damping techniques to the modeling of corrosion damage in structures. Dr. Trego graduated from Brigham Young University in 1997 with a Ph.D. in Mechanical Engineering and an emphasis in material science.

Dansen Brown has over 30 years experience in processing and analyzing dynamics data. He received Bachelor's and Master's degrees in Mathematics from Miami University (Oxford, Ohio) in the late '60s. He has worked for AFRL/VA since 1972, where he develops and maintains an advanced capability for the processing and analysis of dynamics data recorded during flight and ground tests conducted by the Structural Dynamics Branch of the Structures Division. He also frequently develops computer programs to recover, process, and analyze data recorded from other AF programs.

Abstract

The Air Force Research Laboratory (AFRL) sponsored flight tests using on-board state-of-the-art digital data recorders called damage dosimeters to measure temperature and vibration data in areas of acoustic fatigue on the B-52, F-15 and C-130 aircraft. The damage dosimeter, designed by The Boeing Company, measures structural strains and temperatures on in-service aircraft to diagnose difficult-to-analyze structural conditions, such as acoustics and high cycle fatigue. These tests were part of an AFRL Structural Technology and Analysis Program (STAP) to support the durability patch design process to repair structural cracks in secondary structure. The dosimeter measures temperature and 3 dynamic strains for use in the design of damped durability patches. It is a rugged, small, lightweight data acquisition unit that runs off of battery power in an autonomous fashion. The damage dosimeter quickly measures 3 channels of strain at sample rates as high as 15 kilo-samples per second and a single channel of temperature at a sample rate of 1 per 1.3 seconds. The dosimeter only acquires data above a programmer defined rms strain threshold and is currently programmed to store 42 records of time history data each 0.3 seconds long. In addition it is programmed to record and store third octave spectra in its 4-megabyte memory until filled. The damage dosimeter merges the functionality of

both the analog signal conditioning, and a digital single board computer. The entire unit (sans battery) weighs less than 1.5 lb (.68kg) and fits in the palm of your hand. This paper will describe basic damage dosimeter design, data format and aircraft installations and will also provide quick looks at the typical time history and third octave data using LabVIEW™ virtual instruments (VIs). The paper concludes with a typical scatter plot and recommendations for future updates.

Keywords

Dosimeter, Data Acquisition, Durability Patches, Vibration, Acoustics, Strain, Structures, Third Octaves

Introduction

Structural cracks in secondary structure, resulting from a high cycle fatigue (HCF) environment of greater than 10^6 cycles, are often referred to as nuisance cracks. This type of damage can result in costly inspection and repair. Often the repairs do not last long because the repaired structure continues to respond in a resonant fashion to the environment. Although the use of visco-elastic materials for passive damping applications is well understood, there have been few applications to HCF problems. This is because design information characterizing temperature, resonant response frequency and strain levels are difficult to determine. The Durability Patch and Damage Dosimeter Program is an effort to resolve these problems with the application of compact, stand-alone, electronics and a damped bonded repair patch. Typical cracking of secondary aircraft structure is shown in Figure 1.

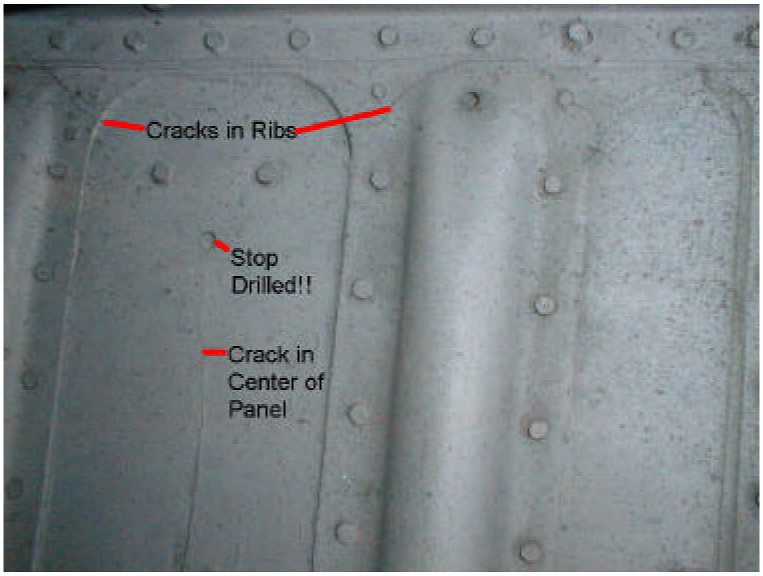

Figure 1. Cracks on Secondary Aircraft Structure.

Since secondary structure is not flight critical, it typically does not carry very high loads and is often minimum thickness (less that 3 millimeters (mm)). The durability patch restores structural integrity and increases the structure's damping in the repair region. Increased damping reduces resonant response, which in turn enables the repair to survive the life of the aircraft. In order to design a repair with effective damping properties, the in-service dynamic structural strains and temperatures must be known. This is because damping material properties are a function of both frequency and temperature. Boeing developed a stand-alone data acquisition system, seen in Figure 2, than can be easily installed on an in-service aircraft and monitor temperature and structural dynamic characteristics. This data

Figure 2. Dosimeter and Battery Pack.

provides the information required to design a repair with optimal strength and damping effectiveness.

There are a number of portable data acquisition systems currently in use in flight tests. One example is documented in by Fing, Brinkley and Wrenne (1998) and Fling and Hostel (1997) during flight testing at Eglin Air Force Base (AFB), Florida. The state-of-the-art in portable data acquisition is constantly changing. The unique features of the damage dosimeter design include autonomous operation, on-board Fast Fourier Transform (FFT) computation and storage of third octave frequency spectra. Also the dosimeter uses the Anderson Current Loop (ACL) for conditioning strain gage signals to minimize the power required to excite the dynamic gages and to eliminate the need to account for wire-length effects. Anderson (1995) describes the ACL technique. For the dosimeter the constant current I = 2 Volts/R_{ref} = 2/350 = 5.7142 milliamps (ma), where R_{ref} = 350 ohms. A typical dosimeter package and battery pack is shown in Figure 2. Smith and Searle (1998) give a complete description of the dosimeter. A photograph and block diagram is shown in Figure 3.

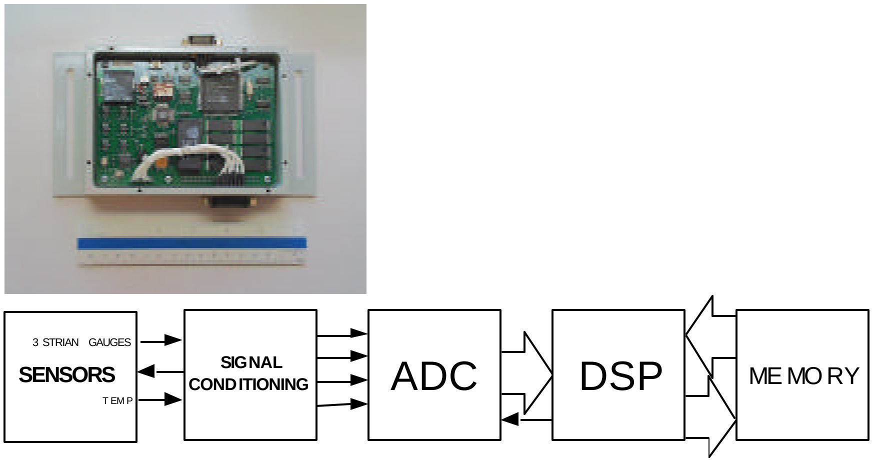

Figure 3. Damage Dosimeter Overview and Block Diagram.

Dosimeter Data Collection, Processing and Recording

The damage dosimeter operates in two modes: shop and acquisition. In acquisition mode the dosimeter acquires and stores data to memory based on preprogrammed parameters. Acquisition mode is activated when the battery pack is connected to the dosimeter and no computer cable is connected to the dosimeter. When a specialized RS-232 cable is connected to the dosimeter, the dosimeter enters shop mode. During this mode dosimeter data may be downloaded from its memory to a personal computer (PC) binary file. Dosimeter memory is then reset before again entering acquisition mode. Once the battery pack is connected, all operations are autonomous (i.e. no human intervention is required) in acquisition mode. For the current memory size of 4 megabytes, it takes about 1.5 hours to download all data from dosimeter memory to a PC file at a fixed rate of 9600 bits per second (bps). Application software can decode the data in the binary file. The dosimeter acquisition parameters can be modified by downloading and reprogramming the dosimeter using C-code to change parameters. Parameters include sample rate, timer settings, third octave start and stop frequencies and others as described by Ikegami, Rogers, Haugse and Trego(2001).

FirstTime Calculation

During the first application of power, the dosimeter loads external variables and calculates the background noise level to determine an appropriate noise threshold. Below this threshold, the data will be regarded as noise and will not be recorded. Multiplying the measured background noise by a programmable factor sets the noise threshold. Once the noise threshold is calculated, it is stored until the dosimeter memory is reset. Having completed the FirstTime procedure, the dosimeter powers down and remains in that state until a watchdog timer (WDT) counts down the idle time and expires again.

Data Collection

When the WDT expires again, the dosimeter will boot, enter acquisition mode (assuming no serial cable connection), bypass the FirstTime subroutine, and begin collecting data strain and temperature data. Dosimeters fabricated to date sample strain data at a rate of 7600 samples per second and temperature at about 1 sample per 1.3 seconds. In addition, a time stamp is collected from the real-time clock.

Data Processing

The raw strain data for each of the three gages is immediately processed through a Fast Fourier Transform (FFT) analyzer to generate a Power Spectral Density (PSD). The PSD is then integrated over 18 discrete frequency bands to obtain a course representation of the vibration environment. Typically these bands are defined to be contiguous 1/3-octave bands. This provides a 1/3-octave band distribution of strain activity across the specified frequency range. The starting point of the 1/3-octave band distribution is programmable. Practical limits on the starting point are between 15 Hz and 75 Hz. Below 15 Hz, the width of the 1/3-octave band is less than the frequency increment of 3.71 Hz (= 7600Hz / 2048). Above 75 Hz, the final 1/3-octave band lies above the Nyquist frequency of 3800 Hz (= 7600Hz / 2). The ending point of the final band is given by:

End Frequency = Start Frequency (of first band) x $2^{(18/3)}$ = Start Frequency x 2^6 = Start Frequency x 64.

The 1/3-octave band distributions for each strain gage are recorded to flash memory for each sample set. Each distribution requires 36 bytes of storage, totaling 108 bytes for all three distributions. In addition, the temperature and time are recorded as well as absolute peak strains on all three gages. Together, these components comprise a standard data record (SDR). The total memory required for one SDR is 122 bytes. The total flash memory available for recording SDRs is approximately 3.6 Mbytes. Therefore, approximately 29,500 SDRs can be recorded before filling memory. At 1.3 seconds per SDR, this represents approximately 10.7 hours of data collection time.

Threshold Comparison

Before the dosimeter records data, the noise threshold comparison is continuously made for each sample set. If the strain activity falls below the noise threshold for a specified number of consecutive sample sets, the dosimeter will stop recording data and power down. This feature prevents data collection and battery drain during periods of low strain activity flight such as cruise.

Before the processed data is stored to flash memory, the dosimeter checks to determine whether the average strain level exceeds the noise threshold calculated in the FirstTime process. The root mean square (rms) of the 18 discrete frequency bands is calculated for each of the three gages, and then averaged to determine the average rms strain level for that sample set. This strain level is measured and averaged over a specified number of sample sets to determine the average level of strain activity over a nominal period of time (a program variable usually set to 3 sample sets). The average rms strain level from those sample sets is compared to the noise threshold. If the current rms strain activity is below the noise threshold, then the dosimeter will power down and remain in that state until the WDT expires again. If the current rms strain activity is above the noise threshold, the dosimeter will begin recording data.

Data Recording

Processed data sets are recorded by writing to non-volatile flash memory. Two types of data records are written: Standard Data Records (SDRs) and Strain Time-Histories (THs). The SDRs primarily consist of the rms strain levels for each of the 18 frequency bands for each gage. In addition, the temperature, time stamp, and maximum strain for each gage are recorded with each SDR. SDRs are recorded only if the rms value of the time history is greater than the noise threshold.

In summary, the data acquisition, processing and recording process time line is as follow: The dosimeter acquires 2048 samples of three strain gages and 1 sample of temperature in about 0.3 second. The PSD is calculated. The rms value is computed and compared to the noise threshold. If the rms value is above noise threshold, the 1/3-octave levels, computed from the PSD, are stored as a SDR record. The first 42 time-history data records are stored as TH records. Acquisition time is about .3 seconds and processing time is about 1 second for each data cycle.

Description of Data Format in Dosimeter Memory

Two types of data records are written to the non-volatile flash memory: Standard Data Records (SDRs) and Strain Time-History (TH) records. To help understand how to read and review damage dosimeter data in the binary PC file, Table I from Ikegami, Rogers, Haugse and Trego (2001) shows the data format. Table I specifically shows the contents of SDR and TH records in the PC binary file for the current dosimeter configuration.

Table I. Content and Size of SDR and TH Records

Standard Data Record		
Element	**Size**	
Time	6	bytes
Temperature	2	bytes
Strain Peaks	6	bytes
1/3-Octave Bands Ch1	36	bytes
1/3-Octave Bands Ch2	36	bytes
1/3-Octave Bands Ch3	36	bytes
Total Record Size	122	bytes
Memory First Address (hex)	10000	
Memory Last Address (hex)	380000	
Total Memory	3604480	bytes
Maximum Number of Records	29544	
Records per Second	1.3	
Maximum Recording Time	10.67	hours

Strain Time-History Record		
Element	**Size**	
Time	10	bytes
Unused	2	bytes
Temperature	2	bytes
Strain Time-Hist Ch1	4096	bytes
Strain Time-Hist Ch2	4096	bytes
Strain Time-Hist Ch3	4096	bytes
Total Record Size	12302	bytes
Memory First Address (hex)	380001	
Memory Last Address (hex)	400000	
Total Memory	524287	bytes
Maximum Number of Records	42	
Records per Second	1.3	
Maximum Recording Time	54.60	seconds

Strain Time History Records

Strain time history records consists of 2048 sample points for each strain gage. The dosimeter is programmed to record the first 42 strain time history records. The strain time-histories contain the raw strain data for each of the three strain gages from one sample set. In addition, the temperature and time stamp for that sample set are recorded for each data set.

Third Octave Records

The SDRs consist of the rms strain levels for each of the 18 third octave frequency bands for each gage. After recording the first 42 records, the dosimeter continues to acquire data, compute an FFT and store third octave records in SDRs in the remaining memory locations. These data sets provide a characterization of the strain environment in the frequency spectrum. In addition, the temperature, time stamp, and maximum strain for each gage are recorded with each SDR.

Current Calibration Information

The calibration information for the dosimeter data in this paper is based on values found in earlier analysis software routines. Also, a method to perform mechanical end-to-end calibration of dosimeter channels is necessary. Mechanical end-to-end calibration is discussed in the Institute of Environmental Sciences and Technology recommended practice by Himelblau, Piersol, Wise and Grundwig (1990).

For the current dosimeter configuration the following calibration equations were used:

Table II. Typical Band Numbers

#	Start Count	End Count
1	6	6
2	7	8
3	9	10
4	11	13
5	14	16
6	17	20
7	21	25
8	26	32
9	33	40
10	41	50
11	51	64
12	65	80
13	81	101
14	102	128
15	129	161
16	162	203
17	204	256

For strain the micro strain ($\mu\varepsilon$) calibration equation is: $\mu\varepsilon(K) = (K-2048)(\text{counts}) * 1.187\ (\mu\varepsilon/\text{counts})$, which implies that $\mu\varepsilon(0) = -2048*(1.187) = -2430.976\ \mu\varepsilon$ and $\mu\varepsilon(4096) = 2430.976\ \mu\varepsilon$. For temperature (T), the calibration equation is $T(K) = (K/4096)*400-273.16$ °C. For example: $T(0C7B_H) = T(3195_{10}) = (3195/4096)*400-273.16 = 38.85$ °C, $T(0) = -273.16$ °C and $T(4096) = 126.84$ °C. There is a span of 400 °C. K is the number of binary counts recorded on the dosimeter for each variable. These calibration equations were used in the quick look software described later.

Third Octave Bands

The start frequency is programmable and there are 18 total bins. Typical assignments of the 18 third octave bins are shown in Table II. In Table II, multiply the start and end counts by 3.71 to obtain the frequency in hertz. Note that the resulting frequency bands may be different than the nominal third octave bands. The dosimeter stores the rms value for each of the 18 dosimeter bands. When the dosimeter data is post processed, the overall rms value can also be computed from the third octave data.

Summary of Dosimeter Data Collection History

Boeing Flight Testing

The Boeing Company used the dosimeter to collect dynamics data on three

Figure 4. Damage Dosimeter Installations in B-52, F-15 and C-130

aircraft: the B-52, F-15 and C-130. Detail description of flight data measured using the damage dosimeter can be found in Ikegami, Rogers, Haugse and Trego (2001). Three service applications used the damage dosimeter and durability patch design process. The first application is a HCF application on the B-52 aircraft's exterior fuselage. After using the damage dosimeter and discussions with the B-52 System Program Office (SPO), a damping treatment was installed on the interior skin of the airplane. The second application evaluated the dynamic characteristics for an F-15 access panel on the underside of the airplane to confirm performance of the damage dosimeter and patch design process with prior known data and to evaluate the use of the dosimeter in a relatively severe fighter environment. The third application evaluated the environment on the edge of the flap well of a C-130 aircraft that has experienced cracking. Turbulent airflow from the prop-wash causes high cycle fatigue in this region. This application is still under development. Pictures of the installation of the damage dosimeter in the three aircraft are shown in Figure 4.

AFRL Laboratory Evaluations

Boeing delivered four dosimeters to AFRL during August 2001. Two dosimeters will be used on a B-52 and two are retained in-house for evaluation. AFRL set up a dosimeter evaluation laboratory to better understand the operation of the dosimeter and to help obtain knowledge to use the dosimeters in field application. A photograph of the laboratory set up is shown in Figure 5. Three strain gages (Measurement Group type CEA-13-062UW-350) were bonded to an aluminum plate and connected to the dosimeter. In addition an AD590 temperature sensor was connected to the dosimeter and exposed to the room environment. After the initial powering up of the dosimeter, the dosimeter computes a threshold strain level.

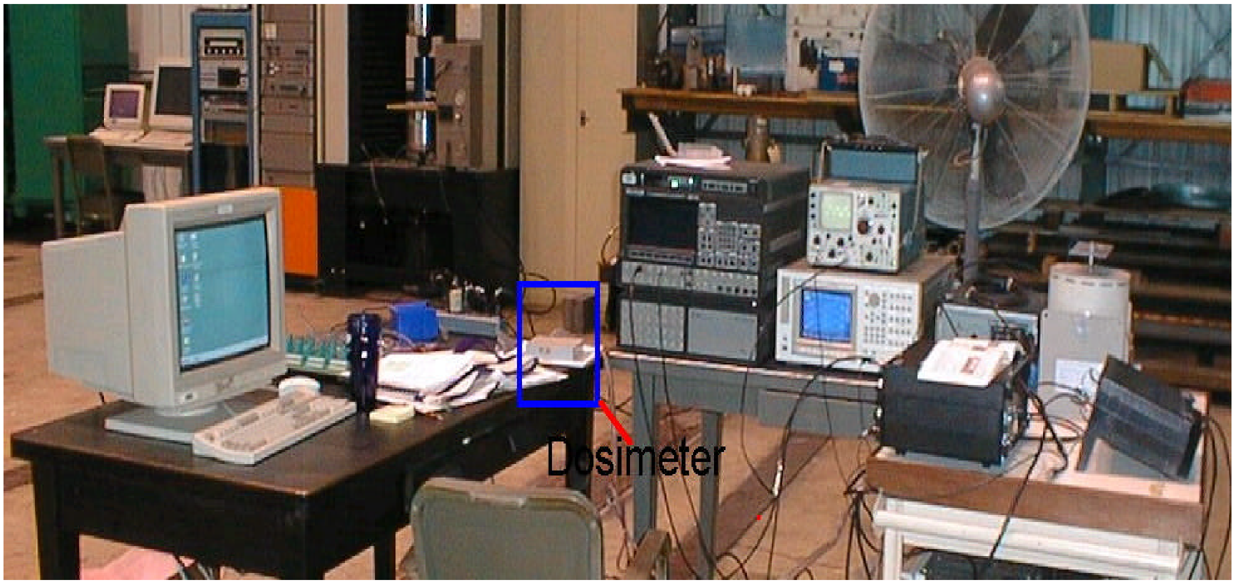

Figure 5. Dosimeter Evaluation Test Setup at AFRL.

Some data were recorded using sinusoidal excitation at the first bending mode of the plate and some data were recorded while the plate was excited with pseudo random noise obtained from the spectrum analyzer to excite multiple vibration modes. In the photograph one can identify the plate on top of the shaker. A +12 VDC and -12 VDC power supply is on the cart shown in the right hand side of the photograph. In the center there is a tape recorder, four channel FFT spectrum analyzer and an oscilloscope for monitoring input and output signals. The dosimeter is located on the table in the left hand side and can easily be connected to a PC for downloading the data from memory.

Software to Do Quick Look of the Data

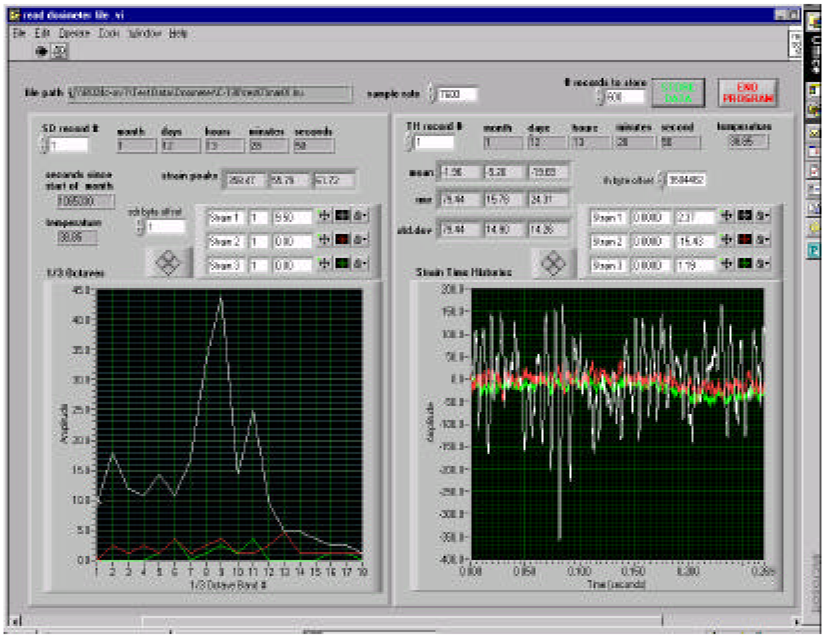

Figure 6. Aircraft Data File Using Quick Look-Version1**.**

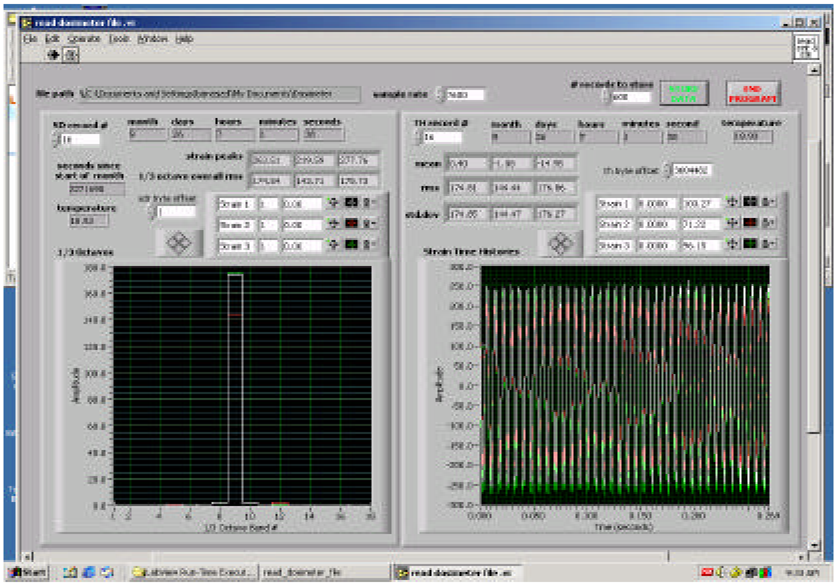

Figure 7. Quick Look at Beam Excited by a Sine Input.

Initial software used to view the quality of dosimeter data was time consuming. Typical dosimeter data reduction using earlier software for B-52, F-15 and C-130 data are shown in Ikegami, Rogers, Haugse and Trego (2001). Since then, Boeing delivered 12 dosimeters to AFRL. AFRL developed software using LabVIEW™ virtual instruments (VIs) to get a quick, efficient look at the data. The first version viewed data from a C-130 to help determine that the onboard dosimeter clock was not functioning. In addition the VI shows the desired TH or SDR records by displaying data from the raw dosimeter data file. A typical output of aircraft data is shown in Figure 6. In version 1, connecting points plotted the third octave data. Later versions of this software provided AFRL with the capability to quickly look at laboratory data while evaluating the dosimeter in its facility. Figure 7 show a quick look at strain data on a cantilever beam excited by a sine input in the laboratory. This newer VI helped AFRL engineers to understand dosimeter operation. The VI allows the user to create a spreadsheet file for desired data records as shown by the portion of the sample sheet shown in Figure 8 for SDR numbers 1-15 for the third octave data. The time (month, day, hour, minute, second), temperature, strain peak 1, strain peak 2, and strain peak 3 is read directly from the binary file obtained from the dosimeter memory. The VI computes the overall

rec #	mo	da	hr	min	sec	sec in mo	temp	strain pk 1	strain pk 2	strain pk 3	oct ovrl 1	oct ovrl 2	oct ovrl 3
1	9	26	7	1	24	2271684	19.516	201.79	170.928	207.725	129.503	108.102	130.667
2	9	26	7	1	25	2271685	19.125	263.514	218.408	275.384	161.628	134.309	162.805
3	9	26	7	1	26	2271686	19.32	290.815	244.522	302.685	193.619	159.195	194.798
4	9	26	7	1	27	2271687	18.832	280.132	242.148	281.319	173.444	142.578	174.626
5	9	26	7	1	28	2271688	19.028	262.327	220.782	273.01	173.477	143.808	174.65
6	9	26	7	1	29	2271689	18.93	258.766	218.408	275.384	173.412	143.696	174.594
7	9	26	7	1	30	2271690	19.32	258.766	219.595	276.571	173.485	142.603	174.683
8	9	26	7	1	31	2271691	19.32	258.766	219.595	274.197	173.485	142.603	174.683
9	9	26	7	1	32	2271692	19.223	261.14	219.595	276.571	173.46	142.588	174.642
10	9	26	7	1	32	2271692	19.32	257.579	220.782	278.945	173.448	143.813	174.683
11	9	26	7	1	33	2271693	19.613	261.14	219.595	274.197	173.493	142.583	174.671
12	9	26	7	1	34	2271694	18.93	258.766	217.221	276.571	173.424	143.764	174.626
13	9	26	7	1	35	2271695	19.32	258.766	225.53	274.197	173.444	143.74	174.602
14	9	26	7	1	36	2271696	19.418	261.14	217.221	277.758	173.456	142.554	174.634
15	9	26	7	1	37	2271697	19.711	262.327	224.343	275.384	173.529	142.618	174.703

Figure 8. Excel Output for First 15 of 29545 SDRs in Laboratory Created using Quick View.

rms strain from the third octave bands. In addition, mean and standard deviation and rms is computed for each of the 42 0.3-second time history records stored in the dosimeter memory.

Preliminary Statistical Analysis

Ikegami, Rogers, Haugse and Trego (2001) show preliminary cross plots of strain versus temperature.

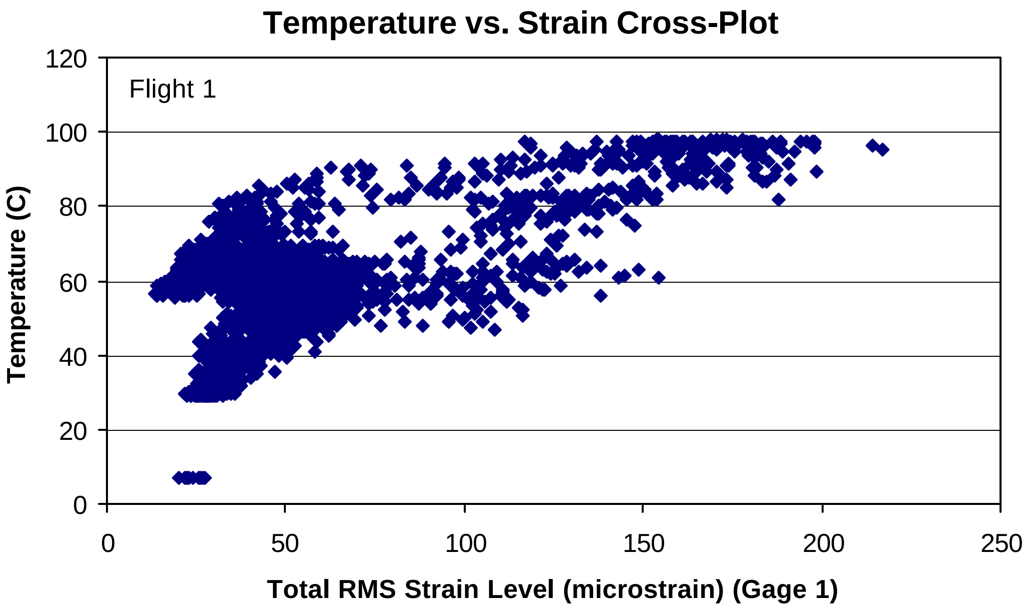

Figure 9. Typical Scatter Plot of Temperature versus RMS Strain Level for C-130 Data.

These are basically statistical scatter plots. A typical scatter plot is shown in Figure 9. In addition, current plans are to use statistical software such as SAS® JMP® to do further evaluation of the spreadsheet data created by the readdosimeter VI. In this plot there appears to be some correlation between temperature and rms strain. One challenge of processing dosimeter data is to determine the actual time since data is not acquired continuously. Future analysis will be done using specialized statistical software programs.

Ideas for Dosimeter Update

Currently AFRL and Boeing are investigating updating the dosimeter via a cooperative research and development agreement (CRADA). There is significant interest in using the damage dosimeter with corrosion sensors and continued interest by commercial companies in evaluating out-of-plane high cycle fatigue in their aircraft fleets.

Based on AFRL's limited experience with the dosimeter the following updates can be considered. The most obvious update is to increase the memory size. Since initial dosimeter design started in 1996, there has been dramatic increase in the capacity of non-volatile flash memory. This would allow more time history records or standard data records. Larger flash memory (up to 256 Mbytes) is already used in commercial off the shelf consumer products such as digital cameras and digital voice recorders. Also, removable or replaceable memory would be quicker for field applications rather than taking the time and extra equipment to do a PC download.

Other suggestions include: 1.) Use 16 bit A-D converters in future version so static and dynamic strain can be recorded on a single channel, 2.) For dynamic measurements, use reusable integrated circuit piezoelectric strain sensors since they are much easier to install than conventional strain gages. There are piezoelectric strain sensors that have a temperature range of –53 to + 121°C. 3.) Sub multiplex low frequency channels such as time, temperature, static pressure, pitot pressure, aircraft accelerations and aircraft rotational rates. Absolute Pressure (Pa or pressure altitude) would be especially useful to ensure that engineers know when the plane is flying, 4.) Increase dynamic channels from three to eight, 5.) Make provisions to use independent Anderson Current Loops rather than a series connection as done for the dosimeter, 6.) Store the standard deviation, mean, rms and peak value in the dosimeter memory. 7.) Store setup and calibration factors in a dosimeter header record. 8.) Store third octave initial bin frequency in SDR record or header record, and 9.) Allow for manual (i.e. non autonomous setting) on/off operation and manual setting strain thresholds, and 10.) Develop and require an end-to-end calibration technique for dosimeter channels after installation.

Summary and Conclusion

The damage dosimeter is a very useful tool to get quick response definition of thermal and dynamic strain frequencies on military and commercial aircraft. The dosimeter may need some updating in the future to be usable on requirements requiring static and dynamic measurements simultaneously.

The dosimeter met all if its design requirements. Twelve damage dosimeters were fabricated for the United States Air Force per the contractual agreement. In-service demonstration of the dosimeter and repair design process was proposed for each of three different aircraft platforms, a B-52, F-15, and C-130. Each of the demonstrations show that 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 an arresting repair.

The dosimeter is very useful as is but there can be some improvements as indicated earlier. The Quick View LabVIEW™ VI developed by AFRL quickly and efficiently evaluates data collected by the damage dosimeter.

Acknowledgments

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