NREL/TP-440-21507 • UC Category: 1210 • DE96007950

Application of BSTRAIN Software for Wind Turbine Blade Testing

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Prepared for
AWEA Windpower '96
Denver, Colorado
June 23-27, 1996

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Prepared under Task No. WE618410

July 1996

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Abstract

The National Renewable Energy Laboratory (NREL) currently operates the largest structural testing facility in the United States dedicated to the testing of wind turbine blades. Recently, a completely new data acquisition system was developed to measure blade response and monitor test status. The system is based on a National Instruments (NI) software package, LabVIEW, and NI hardware components. The NREL custom program is called BSTRAIN (**B**lade **S**tructural **T**est **R**eal-time **A**cquisition **I**nterface **N**etwork) [1]. The objectives of the new software were to develop a robust, easy-to-use computer program that could automatically collect data from static and fatigue blade tests without missing any significant events or overloading the computer system with excess data. The program currently accepts inputs from up to 32 channels, but can be expanded to over 1000 channels. In order to reduce the large amount of data collected during long fatigue tests, several options for real-time data processing were developed including peak-valley series collection, peak-valley decimation, block decimation, and the option for continuous data recording of all data. Other features of BSTRAIN include automated blade stiffness checks, remote terminal access to blade test status, and automated VCR control for continuous test recording. Results from the tests conducted with the software have revealed areas for improvement including test accuracy, post-processing analysis, and further data reduction.

Introduction

For more than five years the National Wind Technology Center (NWTC) at NREL has operated a structural test facility for the testing of wind turbine blades. The first test bay was developed in 1990 when demand for blade testing was relatively low. Until then, laboratory testing of wind turbine blades was not commonly practiced in the United States. This was because it was considered adequate for most wind turbine designs to be proven through prototype field testing and trial and error production experience. Also, there were no other incentives, such as design or type certification, to require companies to test their blades. But perhaps the most significant reason was that the facilities required to test blades did not exist in the United States.

Demand for blade testing has risen sharply in recent years. More facilities with larger and more sophisticated capabilities are in demand due to several factors. First, the current generation of blade designers recognize the limitations of their design tools and the difficulty of implementing a design in production. They have a better understanding of the uncertainties associated with predicting extreme stochastic load events. Thus, the recent trend has been toward laboratory verification and component testing to simulate the entire life under accelerated loading. With this trend has come an increase in the number of blades tested.

The recent shift to international markets for wind energy has also added complexity and urgency to the blade testing issue. Turbine manufacturers wishing to export their turbines to various countries abroad are often required to certify their design in accordance with the established national standard for wind turbine certification. Frequently a blade test must satisfy both the designer, who is interested in verification of design criteria, and a particular code or design standard that may not have been part of the original design requirements. Generally, the influence of certification has mandated higher quality standards for testing and has increased the complexity of testing procedures, demanding more quantifiable results.

Finally, the size of wind turbine blades is increasing. During the past ten years the average blade length has more than doubled with corresponding weights increasing exponentially. These larger blades require higher actuator forces and greater displacements which both drive up the cost of the test equipment and increase the time required to perform a test.

Realizing that structural testing of wind turbine blades can be too expensive for most companies to do on-site, NREL has continued to expand its facilities to meet the growing demand. Presently, the NWTC structural testing laboratory includes two blade test labs. A new 34 meter (120 ft) bay with capabilities to test blades up to 30 meters (100 ft) long will soon be available. The NWTC laboratory has performed full scale structural tests on over forty wind turbine blades from six different turbine manufacturers. The testing capabilities include fatigue testing, static testing, and non-destructive evaluation using several techniques.

One component of the recent facility enhancements includes the development of a new data acquisition system. The primary challenge was to develop a system with the capabilities to sample the real-time data continuously and save only necessary data. For static testing this is fairly straightforward since the test is generally conducted over the span of a few hours. A fatigue test, however, can run for several months, and the amount of data passing through the signal conditioning would overload any system if they were all recorded and stored. The BSTRAIN software was developed as a solution to this problem. The software was designed to minimize the amount of data collected without missing any data that could be needed in evaluating the test.

System Architecture

The Blade Structural Testing Real-time Acquisition Interface Network (BSTRAIN) was developed for the NWTC structural testing laboratory. The development approach was to build a fully integrated data acquisition system using the latest hardware and software available. The new system addresses many problems previously limiting the test lab capabilities ranging from missed data to poor user interfaces. The current system specifications are listed in Table 1.

A schematic showing the NREL fatigue test facilities is shown in Figure 1. The facility uses a closed loop servo-hydraulic system to apply fatigue loading to wind turbine blades. Hydraulic actuators load the blade at a point along its span according to an operator defined displacement profile. The displacements are correlated during quasi-static tests to establish equivalent load levels. A typical fatigue test can last up to several months and several million load cycles. The static testing facilities are identical on the data acquisition side, but use an electric crane attached to a whiffle tree to apply distributed static loads across the length of the blade.

TABLE 1 - BSTRAIN SYSTEM SPECIFICATIONS

General Information

Number of Channels	32 (software limited)
Sampling Frequency	Fatigue - 120Hz/channel Static - 5 Hz/channel

Signal Conditioning

Gain	1 - 500
Bridge Completion	provided in SCXI module
Bridge Excitation	3.3 Volts
SCXI Filtration	10 kHz
Shunt Calibration	Software programmed

A/D Board

Resolution	16 bit
Speed	100 kHz
Input Range	± 5 Volts

Data Storage

Hard Drive	1.2 Gb
Archive	CD ROM read only Erasable Optical Disc

Data Storage (cont.)

Data Files	Binary Data - 2 bytes/sample ASCII Header

BSTRAIN Software

General Features	Graphical User Interface Continuous Test Monitoring Real-time Display - Graphical and Numerical
Static Testing	Standard Deviation and Mean
Fatigue Testing	Real Time Peak/Valley Processing Real Time Decimation Remote Test Monitoring via Modem Continuous Loop VCR Control Automated Stiffness Checking Automatic Signal Zeroing Test Shut Down Triggers - 3 channels Automatic Operator Notification

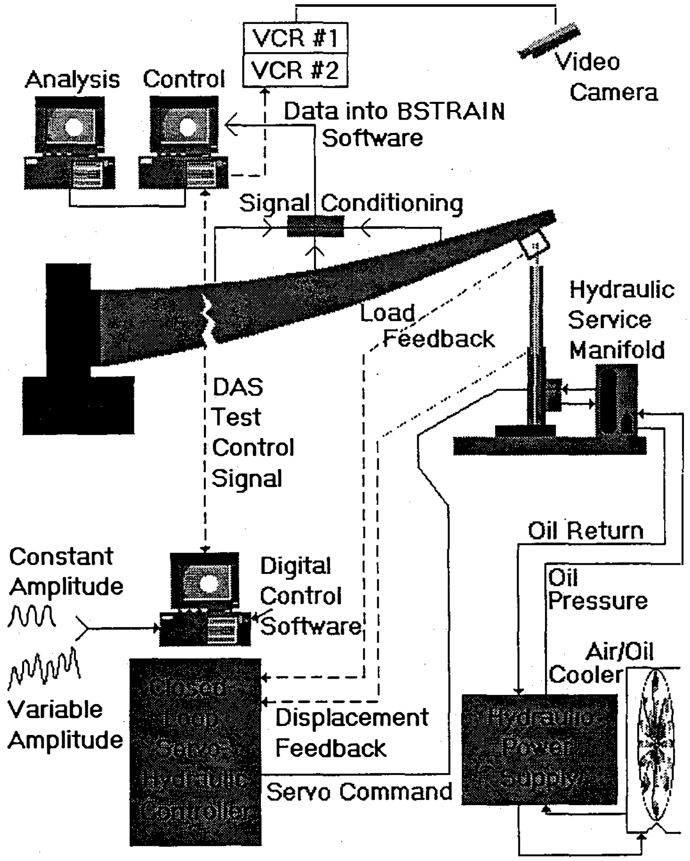


FIGURE I - SCHEMATIC OF NREL FATIGUE TESTING FACILITIES

Each testing laboratory contains a complete system consisting of signal conditioning, a plug-in data acquisition board, and two networked PC's, one for data collection (DAQ) and one for data analysis. The system operates on a NI hardware and software platform. Custom BSTRAIN software, written in LabVIEW, is run on the DAQ computer. Figure 2 shows the generic layout of the **S**ignal **C**onditioning e**X**tension for **I**nstrumentation (SCXI) based data acquisition system used. The BSTRAIN software was specifically designed to receive data in real-time during structural testing of wind turbine blades. Because static tests and fatigue tests differ considerably with respect to their duration and thus the quantity of data collected, the BSTRAIN program treats these tests separately.

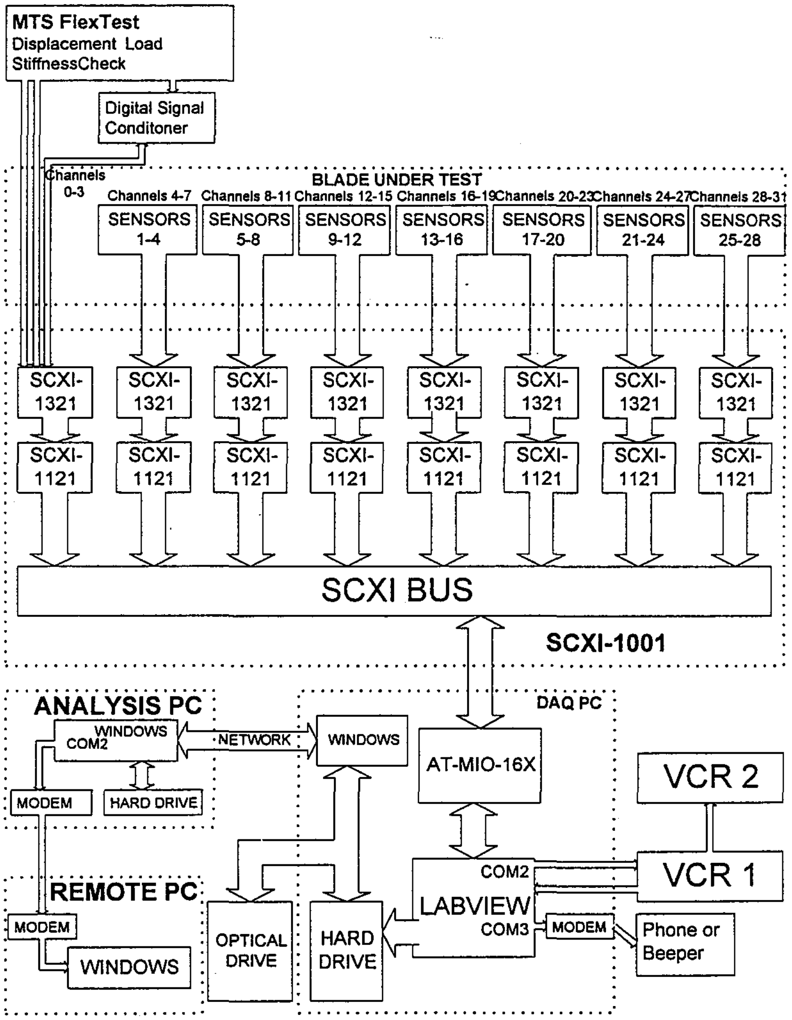


FIGURE 2 - SCHEMATIC OF DATA ACQUISITION SYSTEM

Static Testing

A static blade test usually is conducted to determine the blade's ability to withstand extreme loading. This is done by distributing concentrated point loads along the blade length in a manner which approximates either the blade's design load shape or the blade's design strength distribution. Typically, the loading is increased until a static failure is caused. The results give information on the ultimate strength of the blade, buckling sensitivity, and other likely failure modes. It is extremely important that data is taken continuously without gaps during a static test.

The BSTRAIN static test algorithm collects binary data continuously in real time at a user specified sample rate (typically 2 to 5 Hz) throughout the test. As many as 32 strain gage signals are scaled and shunt calibrated during the initial program set-up. The static load is applied in discrete steps during the test. Displacements are measured and photographs are taken at the plateaus. A time-series file from a typical static blade test is shown in Figure 3. The load measured at the top of a whiffle tree with a three-point distribution is plotted against time for the test duration. The plot shows the increasing blade load steps at regular intervals until failure occurs. Note that the test begins at a non-zero load due to the tare weight resulting from the test fixtures and the weight of the blade itself. The duration of maximum load for this test at the peak load was less than three seconds before failure occurred. It is known that the strength of Douglas Fir, for example, under constant load decreases significantly (8% per decade) with load duration [2]. Therefore, the minimum duration of the target test load should be specified for a static test to avoid ambiguous results.

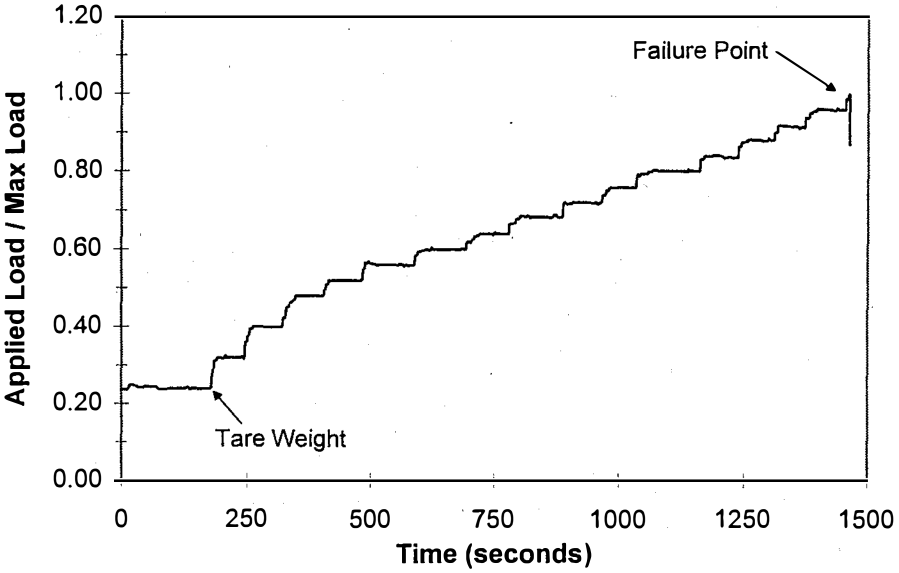


FIGURE 3 - STATIC TEST LOAD TIME HISTORY

In Figure 4, strain measurements are shown on a blade as a function of the normalized applied load during a static blade test. These strains were measured approximately 2.54 cm (1 inch) from the failure location on the compressive side using a rectangular strain gauge rosette for three measurement directions, 0° (longitudinal), 45°, and 90° (transverse). Note that the strain is linear with load at low load levels, but near failure the non-linearity of the strain increases dramatically. The 0° gage shows the greatest non-linearity and some obvious creep behavior at the higher load plateaus.

One useful feature in the BSTRAIN static program is the ability to monitor standard deviations of the measured signals during the test. The program averages each consecutive block of ten samples and computes the mean and standard deviation. Often this additional information provides advanced warning to the test operator of a failure about to occur. For the test data in Figure 4, taken near the static buckle zone, standard deviations increased by more than an order of magnitude in the few minutes before the failure occurred. This gave test operators advanced indication of the failure location, allowing time to make better observations of the final failure.

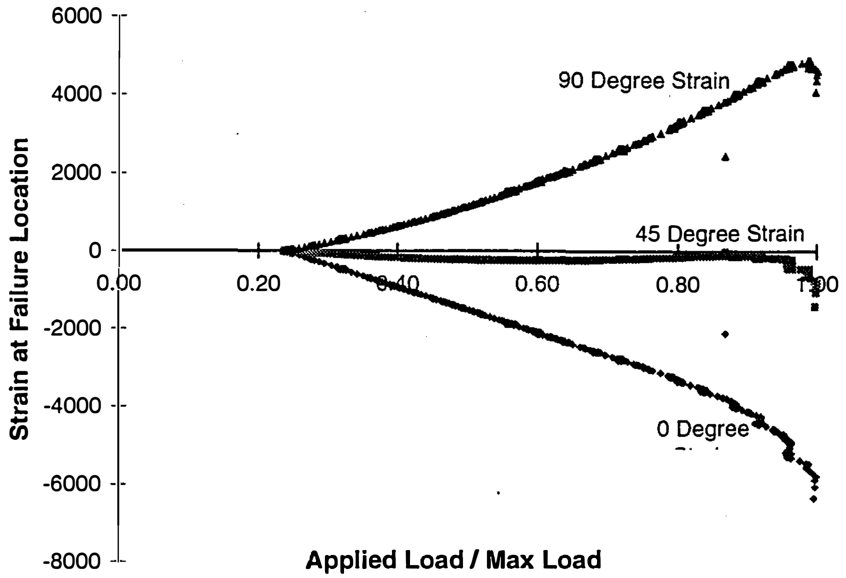


FIGURE 4 - STATIC TEST - STRAIN MEASURED AT FAILURE LOCATION.

Fatigue Testing

A fatigue test is conducted to verify the blade's ability to withstand a spectrum of operating loads that is representative of its design life. Commonly the blade design life is up to thirty years consisting of nearly 10^9 cycles. To achieve a test that is representative, the load is usually amplified to accelerate the test and reduce the number of cycles. Typically this is between 10^6 and 10^7 load cycles. Even with this acceleration, fatigue tests can run for several months. The type of data acquisition program that is required for fatigue tests is therefore quite different than that for static testing.

The primary objective of the fatigue test software was to reduce the amount of data to a reasonable quantity that would not overload the available disk space on a standard PC, but without missing any events that might be important. The minimum requirement was defined as the acquisition of data peaks and valleys for each channel. Although this still results in a large quantity of data, the primary goal was met. Data is stored in 1.4 Mb file sizes in binary format. A FORTRAN conversion routine was written to convert the binary data to ASCII format and download them into an EXCEL spreadsheet.

Normally it is necessary to control the actuator movement and position during a test using displacement rather than load. This is because the actuator force is usually not correlated well with blade strain in the range of frequencies at which blade tests are normally run. As the test frequency approaches the natural frequency of the test specimen, the required load input decreases and the repeatability of load from cycle to cycle is poor [3]. These effects usually make the load signal an unreliable reference for dynamic test control. Therefore, the algorithm is based on the assumption that blade displacement is correlated with blade strains at any cycle frequency. It uses the displacement channel as the master channel to trigger its search for peaks and valleys on the other data channels.

The load, however, is a very important parameter during a fatigue test. Ultimately, the actuator movement is defined by the force applied to the blade under static conditions. To establish the test parameters, displacements are measured statically under the specified test load. The dynamic loading is specified for these statically derived displacement parameters under true load.

The global blade stiffness can be calculated by determining the load required to move the blade a given distance at the load application point under static conditions. As the blade is cycled, this stiffness parameter typically decreases. Rapid drops in stiffness can often be related to a blade failure in progress. Generally, stiffness drops of more than 5% to 10% of the original value will indicate a complete blade failure. Monitoring the blade stiffness is one way to track the health of the test specimen. BSTRAIN has a built in routine for checking the stiffness of a blade during fatigue tests. The operator programs the controller to produce a slow, quasi-static cycle at a prescribed interval during the test. Commonly, this interval is around 1000 cycles. If the slow cycles are applied significantly below the normal cycle frequency, dynamic effects are negligible and an accurate measurement of load versus displacement can be obtained. This is usually 10% of the operating frequency.

The BSTRAIN program computes the stiffness value and writes it to a separate file. During the stiffness check, the MTS program also instructs the actuator to move the blade through its zero strain position. BSTRAIN finds the zero position and corrects all the data channels for any drift that may have occurred. This procedure is illustrated in Figure 5.

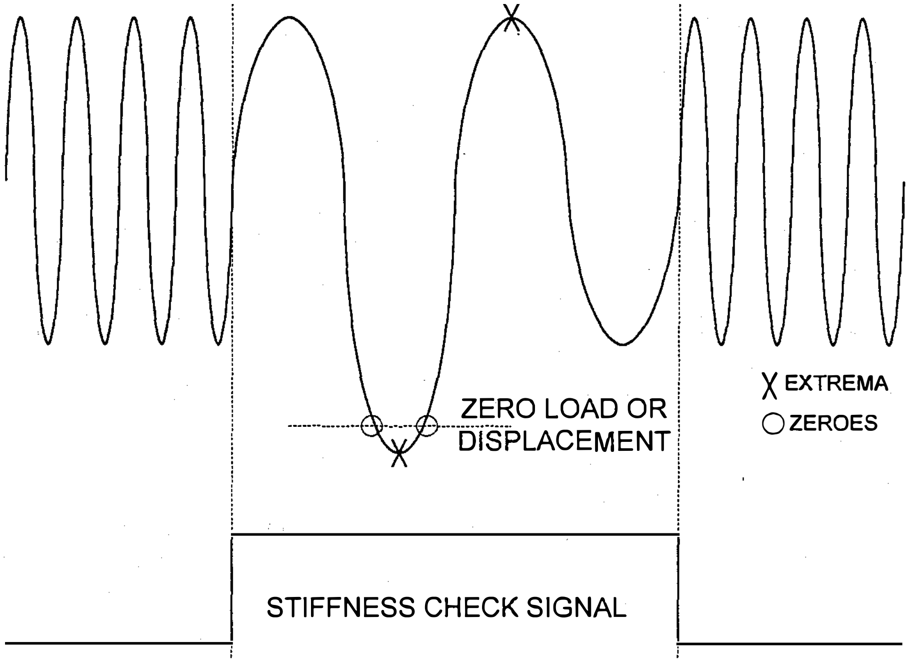


FIGURE 5 - STIFFNESS CHECK AND AUTOZERO

Figure 6 is a plot of the blade stiffness file for an entire blade test. Blade stiffness is normalized about the initial stiffness level. The data illustrate a drop in stiffness of approximately 7% over the test duration. Note that the blade was able to carry the test load for more than 2 million load cycles with a steady but slow decline in stiffness. Near the end of the test, a more overt failure mode caused an accelerated decline in the stiffness which led to the final failure.

One phenomenon noted during the test shown in Figure 6 is the periodic fluctuations that occur approximately every 60,000 cycles. These fluctuations correspond to a diurnal effect caused by thermal effects. Some of this may be due to changes in the blade temperature during ambient day/night cycles, but some is the result of oil temperature changes which affect the LVDT displacement transducer in the actuator. This problem will be thoroughly investigated in the future.

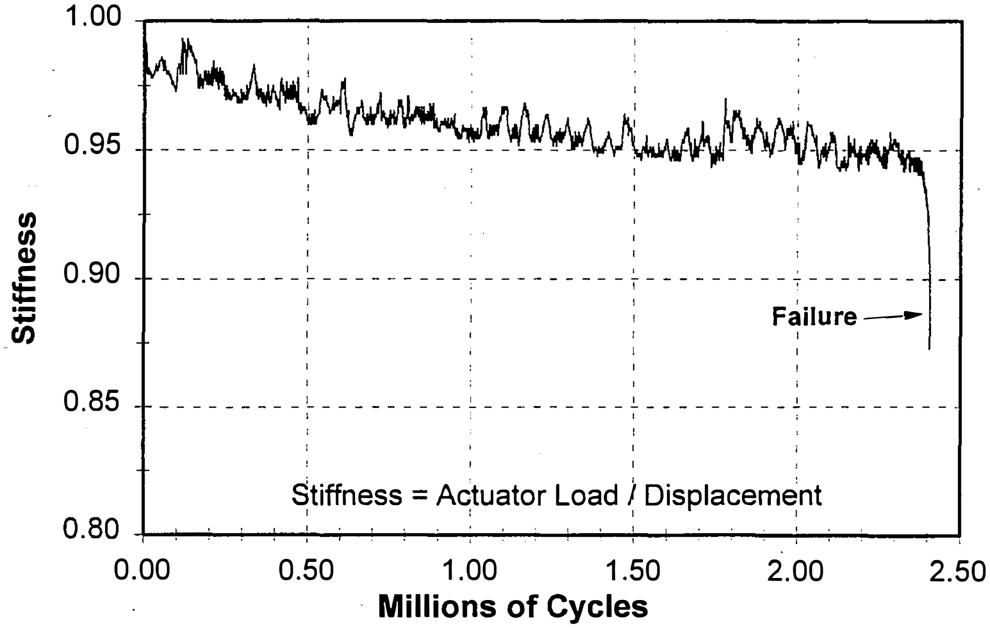


FIGURE 6 - FATIGUE TEST - STIFFNESS TIME HISTORY

Another useful feature allows the operator to print a status file summary printout from the control screen of the BSTRAIN program at any time during the test. This file gives the current values of all the data channels and the current status of the test conditions. This is the fastest way to learn what is happening with a test at any given time. A sample of the status file summary is shown in Figure 7.

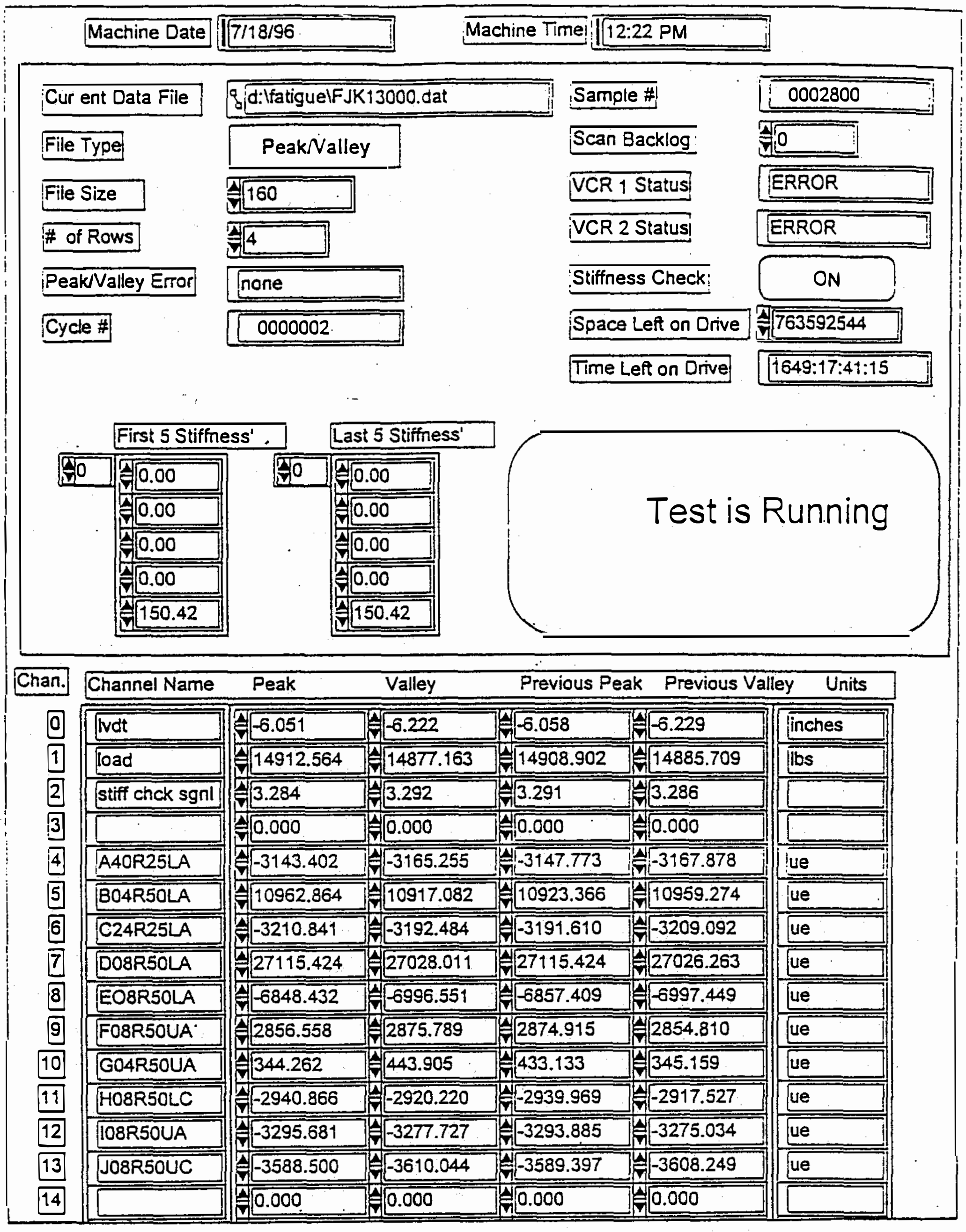
BSTRAIN also allows the operator to access the most recent status file of a blade fatigue test from a remote terminal via modem. An additional custom software package called BSTATUS was developed so that the remote user would not need to install LabVIEW in order to retrieve a status file. During a fatigue test, BSTRAIN writes a status file containing the cycle number, stiffness values, peak/valley channel data, VCR status, and other pertinent information about the state of the test. This file is updated approximately every five seconds, depending on the scanning frequency. In addition, the software can be directed to notify a specified person by telephone if the test is shut down for any reason.

For both static and fatigue tests, continuous video recording of the blade test is controlled by BSTRAIN. For fatigue tests, which run even when no one is present to monitor the test (at night, on weekends, etc.), the software controls two looping VCRs so that no event will be missed due to the rewinding or changing of video tapes. When a major event occurs in the test, such as a sudden drop in stiffness, the test will be automatically shutdown and the VCRs stopped so that the event can be viewed at a later time.

Conclusions and Future Work

Full scale blade testing for design verification and to speed certification approvals will likely become a standard part of the design process and a requirement for international marketing. The BSTRAIN program described in this paper uses the latest technology to boost the quality of blade tests conducted at the NWTC.

As more experience is gained with the current software and data system its limitations have become apparent. Efforts to reduce data to a peak-valley series compression were sufficient for managing



Machine Date	7/18/96
Machine Time	12:22 PM
Cur ent Data File	d:\fatigue\FJK13000.dat
File Type	Peak/Valley
File Size	160
# of Rows	4
Peak/Valley Error	none
Cycle #	0000002
Sample #	0002800
Scan Backlog	0
VCR 1 Status	ERROR
VCR 2 Status	ERROR
Stiffness Check	ON
Space Left on Drive	763592544
Time Left on Drive	1649:17:41:15

First 5 Stiffness'	Last 5 Stiffness'
0	0
0.00	0.00
0.00	0.00
0.00	0.00
0.00	0.00
150.42	150.42

Test is Running

Chan.	Channel Name	Peak	Valley	Previous Peak	Previous Valley	Units
0	lvdt	-6.051	-6.222	-6.058	-6.229	inches
1	load	14912.564	14877.163	14908.902	14885.709	lbs
2	stiff chck sgnl	3.284	3.292	3.291	3.286	
3		0.000	0.000	0.000	0.000	
4	A40R25LA	-3143.402	-3165.255	-3147.773	-3167.878	ue
5	B04R50LA	10962.864	10917.082	10923.366	10959.274	ue
6	C24R25LA	-3210.841	-3192.484	-3191.610	-3209.092	ue
7	D08R50LA	27115.424	27028.011	27115.424	27026.263	ue
8	EO8R50LA	-6848.432	-6996.551	-6857.409	-6997.449	ue
9	F08R50UA	2856.558	2875.789	2874.915	2854.810	ue
10	G04R50UA	344.262	443.905	433.133	345.159	ue
11	H08R50LC	-2940.866	-2920.220	-2939.969	-2917.527	ue
12	I08R50UA	-3295.681	-3277.727	-3293.885	-3275.034	ue
13	J08R50UC	-3588.500	-3610.044	-3589.397	-3608.249	ue
14		0.000	0.000	0.000	0.000	

FIGURE 7 - AN EXAMPLE OF A STATUS FILE SUMMARY PRINTOUT

the data stream into a standard PC but the quantity of data is still too cumbersome. Additional data compression routines are still needed to expedite the dissemination of the data to customers and to allow quick trend analyses to be performed. Quick status file summaries are not sufficient.

Future enhancements that are presently being developed for the next version of BSTRAIN include real time rainflow counting and histogram generation for data channels. Histograms will provide a fast and accurate count of the true cycle count at critical channels. The peak/valley and time series data will still be preserved in case sequence effects or discrete events need to be analyzed. Data channels will also be included as part of the stiffness file checks. This will guarantee that a compressed record of the data will be kept throughout the test.

Acknowledgments

The authors would like to thank the many people who made contributions to this work. Jim Johnson, Mike Jenks, Darren DeShay, Zach Hawkins, Jack Allread, Bob Keller, and Bill Gage were all involved in the success of this project and without them the work could not have been completed. Finally, we would like to thank the U.S. Department of Energy for their funding of this project and their continued support of the these activities.

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