Boresonic System Performance Evaluation Update

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EPRI NDE Center

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ABSTRACT

Turbine rotor reliability and remaining life assessment are continuing concerns to electric utilities. Over the years, boresonic inspection and evaluation have served as primary components in rotor remaining life assessment. The EPRI NDE Center has completed a series of evaluations that began in 1982 that document the flaw detection and sizing capabilities of many boresonic systems. The purpose of these studies is to provide utilities with a better understanding of system performance and lead to improved reliability when predicting rotor remaining life. Each evaluation has been described in separate detailed reports. In 1994, EPRI published a guide that presented the key results of all the evaluations completed until then. In 1996, EPRI performed evaluations of two additional systems. This report provides an overview of the all the system evaluations completed to date. In 1999, Baltimore Gas & Electric initiated an evaluation of their own boresonic system and completed the data collection portion. The evaluation of the detection and sizing results is scheduled to be completed in 2000.

BORESONIC SYSTEM PERFORMANCE EVALUATION UPDATE

Background

The catastrophic failure of the Gallatin rotor in 1974 (1) graphically illustrated the significance of rotor reliability and the need for accurate rotor evaluation methods. In the past, utilities had relied almost exclusively on the original equipment manufacturers (OEMs) to determine the operability of their rotors through nondestructive evaluation (NDE). However, some utilities feel the OEMs may be too conservative in their rotor inspection and analysis methods, possibly causing premature retirement of some rotors. In some cases, this has led to the use of independent commercial testing organizations or in-house utility personnel and resources for NDE and subsequent rotor analysis.

The current trend toward extending the interval between major turbine overhauls has placed additional emphasis on accurate remaining life assessment. To remove conservatism and improve the accuracy and reliability of remaining lifetime prediction, the NDE equipment and procedures must detect the significant flaws in a rotor and accurately define their locations and sizes. These requirements have provided the impetus for improvements in existing test equipment and procedures and for the development of new test systems. In addition, they have led directly to the implementation of test demonstration and system evaluation standards.

The Electric Power Research Institute (EPRI) has sponsored several projects related to improvements in inspection reliability and rotor analysis accuracy. EPRI project RP 502 (2), "Steam Turbine Rotor Reliability", led to the development of the Stress and Fracture Evaluation of Rotors (SAFER) lifetime prediction computer code that allows utilities to perform their own rotor analyses. The development of an advanced boresonic inspection system called TREES (Turbine Rotor Examination and Evaluation System) was also sponsored under RP 502 (3). Built by Southwest Research Institute (SwRI) and owned by American Electric Power, TREES is an immersion system that utilizes focused transducers. The interest generated in this program led to a request from Duke Energy, Carolina Power & Light, and Virginia Electric Power to demonstrate the capabilities of the TREES system. An evaluation of TREES was performed at the EPRI NDE Center using a series of defect blocks fabricated at the Battelle Columbus Laboratory, also under EPRI contract RP 502. An evaluation of the Bore Ultrasonic Computerized System (BUCS), a contact type system, was performed at the same time to enable direct comparison of results from an immersion system (TREES) to those acquired with a contact system (BUCS). Each evaluation was based on over 1500 measurements of known flaws, all lying within 0.5-inch of the bore surface, in a series of bore simulation blocks that were fabricated by a Hot Isostatic Pressing (HIP) process. The results, as published in EPRI report NP-2640 (3), document the repeatability and accuracy of detection and sizing of near-bore flaws for the TREES system.

In 1985, again at the request of several utilities, the NDE Center evaluated another boresonic inspection system. This system, the Phased Optics Computerized Ultrasonic System (PHOCUS), was developed by Westinghouse Electric Corporation (W). It too uses immersed, focused-beam ultrasonic techniques. The PHOCUS system evaluation was based on measurements of the same flaw blocks used in the TREES study. The results of the PHOCUS evaluation were published in EPRI report NP-4167 (4).

Also in 1985, a system built and operated by Public Service Electric and Gas for testing their own rotors was evaluated. The scope of the evaluation procedure was modified to accommodate their specific requirements, and no formal report was issued by EPRI on this evaluation.

A performance evaluation of a TREES system built by SwRI for Taiwan Power was conducted by the NDE Center in 1988 under contract to SwRI. Taiwan Power included the system evaluation as part of the purchase specification under which the system was built. The results of this evaluation can be found in EPRI report NP-6513 (5).

In 1988, EPRI report NP-5948 (6) was published. In this report, an evaluation of a contact boresonic system (BorSonic™) developed by Commercial Machine Works (CMW) was described. Currently, the CMW BorSonic™ system, including the technology, hardware, and patent rights is owned by (W).

In 1992, the EPRI NDE Center completed evaluation reports of boresonic systems owned and operated by Northeast Inspection Services Incorporated (NISI), EPRI report TR-102256 (7); NEI Parsons Limited of Newcastel-upon-Tyne, England, TR-102126 (8); and Duke Energy (PHOCUS System), TR 103342 (9). In 1993, evaluations were completed for the Westinghouse and Dynacon UDPRPS systems, TR-106234 (10). Dynacon Systems and the NDE group of Westinghouse's Power Generation Services Division have since merged to form a new company, Wesdyne International. In 1996, evaluations were also completed for General Electric Company, TR-107174 (11) and Reinhart & Associates, TR-107125 (12).

Each of the above evaluations have been described in separate detailed reports as noted in the references. In 1994, EPRI published the *Boresonic System Performance Guide* (13) that presented the key results of all evaluations completed until then in a condensed form to enable easy comparison of system performance and will be updated from time to time as additional evaluations are completed.

It should be noted that some vendors modified their scanning and evaluation procedures to optimize performance for these particular test blocks. Any exceptions from normal field test practices are described in the individual reports for each system evaluation mentioned above.

Boresonic Evaluation Plan Description

EPRI-sponsored rotor boresonic performance demonstrations began under RP 502 with the development of the TREES boresonic system and the original eight defect blocks. The first demonstration was designed to evaluate the TREES system's focused transducer configuration in an immersion technique and compare the results to the laboratory system, BUCS, that used a more conventional contact method. Data were gathered with both systems and evaluated by the NDE Center. The evaluation plotting routines used at that time were also developed under RP 502 and were designed specifically for the TREES system. The TREES plotting routine places data into three dimensional pixels via a process in which each pixel either contains the apparent source of one or more hits (in which case the pixel is “turned on”) or it contains no data (in which case the pixel is empty or "not turned on"). Signal amplitude and quantity of hits within a given pixel have no further significance. Reflector size estimates are based on the hit envelop, in this case the boundary of the volume of pixels considered to be illuminated by the same reflector. That is, the boundary of contiguous illuminated pixels, with some tolerance for unconnected (but close) illuminated pixels and for nonilluminated pixels within a generally illuminated region, is used to define the reflector. The TREES plotting routine utilizes pixel sizes based on the focal sizes of the beams produced by that system. As successive systems were evaluated, the same procedures continued to be used. The NDE Center evaluated the data by determining detections and sizes of the reflectors derived from their interpretation of data as determined from the TREES plots. It is important to note that the approach used with TREES data to size reflectors is based on the boundary of the hit envelop, as described above, and that all systems evaluated using the TREES plotting routine also used hit envelop as the basic sizing approach.

The validity of the evaluations using the TREES plotting software to evaluate other test systems was questioned from time to time based on the applicability of TREES-based pixel sizes to evaluate non-TREES data. This was investigated and found to be appropriate for the analyses performed and sizing algorithms used by the subject test systems (14). This analysis showed that the approach was valid so long as two conditions were met. First, the beam size of the participating system had to be larger than the TREES beam sizes. Second, the system being evaluated had to estimate flaw size using a hit envelop sizing approach. These conditions were always met for the systems evaluated under this plan.

In addition to the evaluation activities that were performed, a plan by which the validity of each performance demonstration could be verified was also followed in conducting the evaluations. To ensure that the test vendor performed the examinations according to established procedures and to further ensure that the security of the defect blocks was not compromised by performing alternative tests, NDE Center staff would accompany the blocks to the test vendor's site. Depending on the length of time it took to gather data, the cost for this effort could be significant.

Revised Boresonic Evaluation Plan

In 1990, a review of the procedure by which previous boresonic performance demonstrations were performed was conducted. This review was precipitated by two factors. First, a reduction in funding for such activities by EPRI transferred much of the financial burden to the participating vendors and made it extremely expensive for test vendors to demonstrate their test system capabilities. Second, the reflector sizing procedures employed by the NDE Center for earlier evaluations were considered inappropriate in some cases where alternative evaluation procedures had been developed and put into use by various vendors. The NDE Center sizing approach was based on hit envelop. While this sizing approach had been acceptable for the systems evaluated prior to 1990 (because all systems evaluated had used a similar approach), this method is not considered suitable for some of the newer systems being introduced which use echodynamics, statistical approaches, etc. to estimate size. While many factors were included in the reappraisal, it was obvious that the best way in which to factor the effects of system-specific sizing algorithms into the performance demonstration and also to cut the cost of an appraisal is to permit the vendors to do more of the costly data evaluation and sizing steps. As a result, a new performance demonstration plan was developed and implemented. Steps are included in the plan to assure that this is done in a manner that does not compromise the confidentiality of the blocks nor the integrity of the results.

The procedure was modified and key changes were incorporated as follows:

- Where possible, responsibility for the activities that were the most labor intensive for Center personnel have been transferred to the participating vendor or their delegate. This means that Center staff will no longer accompany the blocks and witness the data acquisition phase of an evaluation at the vendor's site. However, the security of the blocks and their continued maintenance remain the responsibility of the EPRI NDE Center. The security of the blocks is accomplished by a system of strategically placed lead seals at locations where the fixture that houses the blocks are coupled together. When the test fixture is returned to the NDE Center, any sign that the seals have been tampered with or that supplemental bore examinations, for example using penetrant or magnetic particle inspection, have been conducted will invalidate the examination.
- Another major cost reduction step involves the data reduction portion of an evaluation. The evaluation of the data to determine detection performance and flaw sizes and locations, previously performed by Center staff, will now be performed by the vendor. This is a major change in procedure because it effectively makes the vendor's data evaluation an integral part of the total evaluation of the system. This change was made not only to reduce costs but also for technical reasons. As described earlier, the adequacy of the size estimates made by the NDE Center for earlier evaluations was demonstrated, but is only considered appropriate for systems that use a hit envelop approach to sizing. However, as new testing and sizing philosophies emerge, it becomes increasingly difficult to provide identical analyses to those performed by the vendor. The logical choice was to transfer this function to the vendor, as the sizing function would be performed, in fact, in a rotor analysis.
- To validate the sizing analysis performed by the vendor, the new evaluation plan requires that a complete set of all raw data be sent to the NDE Center immediately at the conclusion of the data acquisition phase of an evaluation. In addition, the vendor must either describe their data reduction methodology or submit algorithms. The NDE Center then spot checks the detection and sizing results for accuracy.
- EPRI NDE Center coordinates the overall program for each vendor, identifies the locations in the blocks where the vendor should perform their evaluations, performs the statistical analysis of the evaluation, and writes the final report.
- The Center also determines, on a case by case basis, if it is possible to reduce the total number of scans that a vendor must perform to complete a performance demonstration.
- EPRI publishes the final report.

Test Sample Description

All of the experimental measurements in the evaluation were performed using nine bore blocks fabricated at the Battelle Columbus Laboratory and the EPRI NDE Center. The original eight blocks were fabricated as part of RP 502. In 1988, a ninth block was fabricated at the NDE Center as part of RP 2481-5 and added to the original eight blocks for use in future evaluations. All blocks were made from CrMoV material from a retired rotor. After flaws were fabricated in segments of the rotor material, the segments were HIP bonded together and machined to form blocks with 4-inch diameter central bore holes. The RP 502 blocks contain surface-connected fatigue cracks, subsurface glass beads, and subsurface disk shaped reflectors lying in radial-axial planes. The RP 2481-5 block contains the same types of defects as the RP 502 blocks, with the exception of surface connected fatigue cracks, but the flaws are positioned deeper in the material, i.e., further radially from the bore surface. Together the blocks contain approximately 70 intentional flaws plus several naturally occurring defects in the parent rotor material and at the segment bond lines. It should be noted that the evaluation plan requires that the inspection vendor demonstrate how they determine flaw sizes from the raw data. The NDE Center then spot checks the detection and sizing results for accuracy. Therefore, the information provided in the report does not compromise the integrity of any future evaluations.

In an evaluation, the participating vendor is asked to evaluate some of the naturally occurring flaws and some areas having no apparent flaws to protect the confidentiality of the blocks. However, only the intentional defects are used in the evaluation.

The nine EPRI flaw blocks are clamped together in a fixture to form a continuous bore. The fixture was designed, fabricated and donated to the EPRI NDE Center by Carolina Power & Light. A flange on the reference end of the fixture simulates the coupling of a rotor and provides an adaptor to interface the drive mechanism to the fixture. Together with lead-in adaptors on either end of the blocks, the flange plate, and the blocks themselves, the assembled fixture forms a test piece with a bore approximately 45 inches long. The blocks can be repositioned and rotated to mix the order of the flaws from one evaluation to the next.

Evaluation Results

To date, a total of thirteen evaluations have been performed. This section presents a condensed presentation of the results of the eleven previously published evaluations to enable system comparisons. The complete individual system evaluation reports are available from EPRI.

The data collected from the runs of the EPRI flaw blocks is typically presented in two forms. The detection results are presented in tables for each of the four flaw types. The flaw size measurements are depicted in graph form to show measured versus true size. In the plots, each flaw is represented by a bar with three tics along its length. The center of the bar represents the mean value for that flaw and the ends of the bar represent 1 standard deviation on either side of the mean based on the spread in the 25 scans. Longer bars indicate less repeatability. In addition, the results obtained from the RP 502 blocks have been reported separately from the results obtained from the RP 2481-5 block. This was done to permit a comparison with test systems that were evaluated prior to the addition of the RP 2481-5 block.

Another variation from earlier evaluations involves the size estimates for the embedded reflectors. In earlier evaluations, only the radial extent was considered. However, some practitioners have indicated a preference for considering the axial dimension in the overall size estimate. Consequently, size estimates based on ΔR and on ΔZ are included.

Some of the embedded reflectors are arranged in groups in the blocks for use in assessing system resolution. Several axial groups (i.e., at the same R and θ locations and closely spaced in Z), several circumferential groups, and a single radial group are included for this purpose. In defining the boundaries of the volumes to be considered by the test vendor in their detection and sizing analysis, each group is identified as a single volume to see if the data processing procedure employed to cluster and size flaws could separate the individual reflectors.

Near-Bore Results (RP-502 Blocks)

Detection Results

Detection performance for the near-bore flaw blocks is presented in Table 1. Shown are the detection rates for the three different flaw types; fatigue cracks, embedded beads, and embedded disks. For most systems, detection performance was fairly high, particularly for the surface-connected fatigue cracks.

Table 1: Detection Performance for Near-Bore Reflectors

	Fatigue Cracks (%)	Beads (%)	Disks (%)
CMW	94	95	86
WesDyne (UDRPS)	95	100	100
NEI Parsons	93	98	93
NISI	92	80	71
PHOCUS (1985)	98	100	99
PHOCUS (1993)	100	100	100
TREES (1982)	100	100	98
TREES (1989)	100	100	95
Westinghouse	92	98	80
General Electric	99	100	89
Reinhart & Assoc.	95	100	79

Fatigue Cracks

Fatigue crack sizing performance for each of the systems is shown in Tables 2 and 3 for crack depth and length, respectively. Recall that the correlation coefficient represents how well the data fit the regression line, while the slope and intercept are indicative of any systematic error. Standard deviation and rms error are measures of the spread and accuracy, respectively, in the data. The term RMSE_line represents the error between the measured values and the best fit line. The RMSE_line term was introduced during the revised evaluation plan to quantify the error associated with the best fit line for the benefit of those who may use the linear regression results to evaluate systematic error of their test equipment. Ideally, the fit line would have a slope of one (1.0) and an intercept of zero (0.0), the standard deviation and rms error would be zero (0.0), and the correlation coefficient would be one (1.0).

Table 2: Fatigue Crack Depth Statistics (RP 502 Blocks)

	Slope	Intercept (inches)	Correlation Coefficient	RMSE_line (inches)
CMW	0.450	0.070	0.180	-
WesDyne (UDRPS)	0.609	0.038	0.634	0.066
NEI Parsons	0.300	0.118	0.339	0.072
NISI	0.555	0.053	0.514	0.079
PHOCUS (1985)	1.160	-0.020	0.850	-
PHOCUS (1993)	1.258	-0.014	0.909	0.053
TREES (1982)	0.960	0.090	0.860	-
TREES (1989)	1.040	0.050	0.930	-
Westinghouse	0.562	0.033	0.419	0.105
General Electric	1.060	-0.010	0.995	0.031
Reinhart & Assoc.	0.637	0.100	0.579	0.079

Table 3: Fatigue Crack Length Statistics (RP 502 Blocks)

	Slope	Intercept (inches)	Correlation Coefficient	RMSE_line (inches)
CMW	0.568	0.313	0.467	-
WesDyne (UDRPS)	0.635	-0.102	0.745	0.170
NEI Parsons	0.984	-0.095	0.744	0.253
NISI	1.113	-0.176	0.908	0.142
PHOCUS (1985)	1.240	-0.185	0.930	-
PHOCUS (1993)	1.164	-0.141	0.969	0.097
TREES (1982)	1.040	-0.030	0.990	-
TREES (1989)	1.110	-0.031	0.990	-
Westinghouse	1.046	-0.269	0.729	0.285
General Electric	1.092	-0.080	0.950	0.117
Reinhart & Assoc.	1.131	-0.160	0.863	0.195

Embedded Beads

As mentioned previously, a few of the beads are grouped together into an axial alignment to assess system resolution. With some test systems, the combination of beam resolution, axial index, and the link-up algorithm used to size the defects has prevented resolution of the individual reflectors and grouped these beads together. Consequently, for the purposes of the bore evaluations, the axially grouped beads have been typically handled separately as groups rather than as individual reflectors within the group. To facilitate comparison, the values shown in the following tables include the individually resolved beads only. Table 4 shows the evaluation results for embedded bead diameter. Table 5 shows the results for the bead-to-bore ligament results.

Table 4: Bead Diameter Statistics (RP 502 Blocks)

	Slope	Intercept (inches)	Correlation Coefficient	RMSE_line (inches)
CMW	-	-	-	-
WesDyne (UDRPS)	0.952	0.063	0.651	0.059
NEI Parsons	0.478	0.082	0.400	0.058
NISI	1.350	-0.066	0.756	0.060
PHOCUS (1985)	-	-	-	-
PHOCUS (1993)	1.073	0.0	0.597	0.068
TREES (1982)	0.680	0.073	0.570	-
TREES (1989)	1.690	0.001	0.730	-
Westinghouse	0.960	0.010	0.783	0.041
General Electric	0.817	0.040	0.653	0.044
Reinhart & Assoc.	0.875	0.040	0.832	0.027

Table 5: Bead-To-Bore Ligament Statistics (RP 502 Blocks)

	Slope	Intercept (inches)	Correlation Coefficient	RMSE_line (inches)
CMW	0.016	0.004	-0.710	-
WesDyne (UDRPS)	0.922	-0.016	0.654	0.041
NEI Parsons	0.253	0.0	0.432	0.020
NISI	0.913	0.009	0.893	0.019
PHOCUS (1985)	0.370	-0.010	0.580	-
PHOCUS (1993)	0.809	-0.013	0.664	0.029
TREES (1982)	0.860	0.020	0.810	-
TREES (1989)	1.026	-0.021	0.810	-
Westinghouse	0.250	0.003	0.569	0.014
General Electric	1.050	0.010	0.753	0.031
Reinhart & Assoc.	0.460	-0.010	0.596	0.022

Embedded Disks

Tables 6 and 7 show the sizing results for the data set that also excludes the unresolved disks in the axially aligned clusters. Shown respectively in the tables are: disk diameter based on radial dimension; and ligament between the bore and the nearest side of the disk.

Table 6: Disk Diameter Statistics (RP 502 Blocks)

	Slope	Intercept (inches)	Correlation Coefficient	RMSE_line (inches)
CMW	0.453	0.011	-0.210	-
WesDyne (UDRPS)	0.175	0.116	0.274	0.071
NEI Parsons	0.531	0.051	0.622	0.075
NISI	0.583	0.002	0.654	0.076
PHOCUS (1985)	1.180	-0.084	0.770	-
PHOCUS (1993)	1.120	0.040	0.957	0.039
TREES (1982)	0.700	0.125	0.750	-
TREES (1989)	0.980	0.019	0.830	-
Westinghouse	1.520	-0.141	0.911	0.079
General Electric	0.813	0.040	0.888	0.049
Reinhart & Assoc.	0.136	0.080	0.253	0.063

Table 7: Disk-To-Bore Ligament Statistics (RP 502 Blocks)

	Slope	Intercept (inches)	Correlation Coefficient	RMSE_line (inches)
WesDyne (UDPRS)	0.215	0.082	0.128	0.059
NEI Parsons	1.064	0.010	0.421	0.080
NISI	2.943	0.022	0.696	0.114
PHOCUS (1993)	0.790	-0.006	0.717	0.026
Westinghouse	-0.047	0.054	-0.029	0.060
General Electric	1.315	0.000	0.662	0.053
Reinhart & Assoc.	2.438	-0.020	0.498	0.140

Deep-Seated Flaw Results (RP-2481 Block)

In 1988, a ninth block was fabricated at the NDE Center as part of RP 2481-5 and added to the original eight blocks for use in subsequent evaluations. The purpose of this block was to extend the range of available reflectors to a depth of approximately 4 inches to enable evaluation of system performance on deep-seated flaws. Overall detection performance for the deep-seated flaw blocks is presented in Table 8.

Table 8: Detection Performance for Deep-Seated Reflectors

	Beads (%)	Disks (%)	Axial Group (%)
WesDyne (UDRPS)	100	100	100
NISI	82	46	100
PHOCUS (1993)	70	34	100
Westinghouse [1]	87	67	100
General Electric	83	50	100
Reinhart & Assoc.	78	100	100

[1] Partial dataset includes reflectors from 0 - 2 inch depth.

Conclusions

Since 1982, the EPRI NDE Center has performed thirteen boresonic system evaluations, which represent the majority of systems commercially available in the U.S. In 1990, the procedures followed for evaluating rotor boresonic performance capabilities were changed to transfer a greater portion of the data analysis function to the participating vendor. This change from previous policy was instituted so that the evaluation results would better reflect the complete analysis that a vendor would provide in a real rotor inspection and also to reduce the cost of an evaluation.

In 1994, EPRI published a guide which presented a condensed tabulation of the results of all evaluations performed until then to provide a ready comparison of system performance. In 1996, EPRI evaluated two additional systems and in 1999 Baltimore Gas & Electric initiated an evaluation of their own system which should be completed in 2000.

It should be noted that some vendors modified their scanning and evaluation procedures to optimize performance for these particular test blocks. Any exceptions from normal field test practices are described in the individual system evaluation reports.

These evaluations continue to be beneficial to utilities as a measure of system performance based on common standards. Test vendors have also benefited by gaining additional insight into the performance of their systems.

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