Proposed Update of SAFER-PC Rotor Life Assessment Code

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ABSTRACT

Evaluating the remaining life of power plant turbine and generator rotors is a perennial dilemma facing utility engineers. Extended operation of a critically flawed rotor can result in catastrophic failure. Conversely, premature retirement of equipment burdens a utility financially. With today's pressures to reduce operation and maintenance costs, life extension and maintenance of plant components is receiving considerable attention. Accurate component life assessment is crucial in developing a technical basis for extending the time between major overhauls. Life assessment is multi-disciplinary, requiring knowledge of materials, stress analysis, material property measurement, nondestructive testing, and fracture mechanics analysis.

The EPRI Stress and Fracture Evaluation of Rotors (SAFER) mainframe computer program was used by dozens of utilities to make reliable run-retire-repair decisions. Now, utility engineers can use SAFER-PC, an enhanced personal computer version of the same program, to make independent, unbiased assessments of the remaining life of turbine or generator rotors. These assessments can supplement or replace equipment manufacturers' recommendations. This report will provide an overview of the capabilities of the current version of the PC version of SAFER and summarize proposed improvements to update the code and facilitate ease of use.

PROPOSED UPDATE OF SAFER-PC ROTOR LIFE ASSESSMENT CODE

Background

It is estimated that the SAFER code (1) has been used in the remaining life analysis of over 100 turbine and generator rotors by various utilities and consulting firms. However, its general application was hampered by its restriction to mainframe computers. Performed under EPRI contract RP-2481-6, SAFER-PC eliminates the mainframe constraints imposed on previous versions of the code, thereby increasing user accessibility and facilitating the performance of rotor remaining life evaluations.

The original SAFER code was developed for EPRI between 1976 and 1980 in response to industry concerns following the TVA Gallatin IP/LP rotor failure (2). At this time, the general concern centered over the effects of cyclic operation at elevated temperature on forgings produced from air-melted ingots. The goal was to provide a computer code for the utility engineer that would provide relevant information to decisions concerning inspection intervals and remaining useful life, as governed by the duty cycle severity and frequency.

SAFER-PC combines transient thermal-elastic finite element stress analysis, fracture mechanics, material property data, and the interpretation of inspection data to assess the remaining useful life of steam turbine or generator rotors. Improvements to the code since its inception include:

- incorporating the effects of creep and creep-fatigue interaction on defect growth
- the evaluation of generator rotors
- the ability to perform probabilistic remaining life evaluations
- the evaluation of shrunk-on disk keyway stress corrosion cracking
- the evaluation of crack growth from heat and seal grooves
- the evaluation of crack initiation and growth in high-temperature blade attachments

SAFER-PC is a collection of programs that are linked together through the EPRIGEMS Module running under Microsoft Windows. The EPRIGEMS Module is the cornerstone of the code, guiding the user through the data input, analysis execution, and results review processes, in addition to providing file maintenance and on-line help capabilities. For users who are not familiar with Windows, or who do not wish to convert from DOS, each of the three analysis modules; Stress and Temperature, Blade Attachment, and Remaining Life can also be executed from the DOS prompt.

The analysis modules of SAFER-PC; Stress and Temperature, Remaining Life, Blade Attachment, and post-processing are accessed individually through the EPRIGEMS module, based on selections made by the user. The EPRIGEMS module acts as the user interface for data input and analysis control. Through the incorporation of off-the-shelf graphics packages the time-temperature-property data required for an analysis can be reviewed graphically and a hardcopy made prior to performing the analysis. On-screen mesh geometry and color contour plotting is provided through the post-processing module, allowing black-and-white or color hardcopies of results through Windows-supported printers.

Program Capabilities

The following sections provide a summary of SAFER-PC's analysis capabilities as described in the *SAFER-PC User's Guide & Technical Reference* (3). Detailed operation instructions and technical background of analysis methods are also given in the manual.

Stress and Temperature Module

This module of SAFER-PC consists of the original SAFER code that performs the finite element model generation and transient thermal stress analysis of steam turbine rotors; closed-form stress analysis of generator rotors; and iterative linkup analyses of boresonic NDE data. New to the program is the incorporation of the evaluation of shrunk-on disk keyway cracking from stress corrosion.

The Stress and Temperature module of SAFER-PC is designed to analyze the typical duty cycle of a steam turbine or generator rotor. Steam turbine rotor analysis is accomplished by the generation of a finite element (FE) mesh to represent the rotor geometry. For analysis of generator rotors, a closed-form solution algorithm is used to compute hoop stresses at locations within the rotor body. Since closed-form solutions are used for generator rotors, many of the options and inputs required for FE model analyses are not necessary. Consequently, there are marked differences in the input files used to analyze the two rotor types.

For analysis of turbine rotors, the Stress & Temperature module is designed to analyze a unit duty cycle for:

1. Transient and steady state thermal distributions
2. Stresses due to thermal and centrifugal loads
3. Clustering and iterative linking of boresonic NDE data (deterministic and probabilistic)

For analysis of generator rotors, the S&T module is designed to analyze a unit for:

1. Stresses due to centrifugal loads in the journal and field regions of the rotor. Stresses are determined as a function of circumferential location, accounting for stiffness variation in the generator rotor cross-section
2. Clustering and iterative linking of boresonic NDE data (deterministic and probabilistic)

Boresonic NDE Data Processing

The evaluation of inspection data is one of the most important aspects of performing a rotor reliability evaluation. Over the last ten years, inspection systems have continued to improve and now detailed fatigue/fracture analyses of a rotor can be performed after thermal and stress solutions have been generated and saved.

The Linkup algorithm used by SAFER-PC is an extension of the cluster routine contained in the original SAFER code. In brief, a linkup analysis determines whether individual neighboring volumetric indications (defects) should be considered as one larger defect for the purposes of remaining life calculations. The procedure used to perform this determination has been shown to provide very conservative results (i.e. over-estimating the size of linked-up defects). However, since the evaluation is dependent on the quality of the boresonic data obtained, the developers have hesitated in eliminating some of the conservatism contained in the procedure. Instead, the user is given the tools (parameter options) that allow a reduction in the "safety factor" applied in any given calculation.

Linkup of either spherical or non-spherical data can be performed. The original SAFER code utilized an effective flat bottom hole diameter (EFBD) to size each indication based on the EPRI-developed TREES inspection system (4). Several inspection vendors now process their data near real time and provide tabular results of the location and size of defects in the rotor. These defects are almost always elliptical. To provide a means to perform linkup analyses of these types of data, the option has been added to SAFER-PC to recognize non-spherical data.

Linkup evaluations can be performed deterministically or probabilistically (spherical data only). In deterministic linking, the defect sizes, stress, and temperature conditions are treated as known, non-random variables. In deterministic analyses a maximum of 30,000 indications can be evaluated concurrently. In probabilistic linkup calculations, defect size, stress, and temperature are treated as random variables in a Monte Carlo solution procedure with mean values and standard deviations specified by the user. In probabilistic evaluations a maximum of 200 indications can be evaluated concurrently for up to 10,000 linkup simulations.

Remaining Life Assessment

The fracture mechanics capabilities of SAFER-PC are contained in the Remaining Life Module or PERL Module. PERL is an acronym for Probabilistic Evaluation of Rotor Lifetime. The PERL Module performs deterministic or probabilistic assessments of remaining lifetime of turbine and generator rotor bodies and shrunk disks. The following features are available in the PERL module of SAFER-PC:

- Probabilistic fracture mechanics evaluation of crack growth in steam turbine and generator rotor bodies from both creep and fatigue mechanisms, using either a Monte Carlo technique or an approximate Fast Probability Integration (FPI) method.
- Analysis of shrunk-on disk keyway cracking, incorporating crack growth due to stress corrosion cracking (SCC) for a user-specified disk keyway stress concentration factor, k_t and radial variation.
- Analysis of heat groove and seal groove cracking, incorporating crack growth due to fatigue, creep, and creep-fatigue interactions.

Rotor failure probability is computed using either a Monte Carlo or FPI method of simulating rotor lifetime using statistical distributions of material properties, stress and temperature, and flaw size. For near-bore and rotor periphery cracking, rotor life calculations include crack growth due to creep, fatigue, and creep-fatigue interactions. Transitioning of sub-surface cracks to bore-connected cracks is also simulated during crack growth. For cracks at the inside surface of shrunk-on disks, simulations include crack growth due to stress corrosion cracking (SCC) only, because crack growth due to creep/fatigue in shrunk-on disks has been shown to be insignificant relative to high SCC growth rates (5). Resulting cumulative failure probability distributions can aid in cost/risk decisions regarding inspection intervals and rotor retirement. Conventional conservative deterministic calculations of crack growth can be performed by setting the standard deviations of all random variables to zero and using conservative estimates of mean values.

Blade Attachment & Disk Keyway Analysis

SAFER-PC contains a Blade Attachment Analysis Module. This module performs deterministic creep crack initiation and propagation life calculations for blade attachment hooks. Stress relaxation as a function of time due to creep is accounted for in both the crack initiation and propagation phases of the analysis. Creep stress relaxation and redistribution is performed using an "equivalent plasticity" approach. Creep crack initiation calculations are based on a bi-linear Larson-Miller creep rupture model that includes the effects of triaxial stress states. Creep crack growth calculations can be performed using either Riedel's $C_{(t)}$ (6) or Saxena's C_T (7) as the crack driving force parameter. The Blade Attachment Module can be executed from the SAFER-PC Windows-based EPRIGEMS Module or in a batch mode from the DOS prompt. Default values are provided for all required inputs.

For evaluation of shrunk-on disks, stresses obtained from the Stress &Temperature Module are treated as nominal values that are modified by a stress concentration factor, k_t. This is necessary since the details of the disk keyway geometry are not included in the Stress &Temperature finite element model. Due to the local nature of the stress concentration, its magnitude will decrease with radial distance away from the keyway. In the PERL Module the user can specify both the magnitude of the k_t and its rate of decrease with radial distance from the keyway, for each disk using a fourth order polynomial.

Proposed Improvements to SAFER-PC

Following is a summary of proposed improvements to be made to the SAFER-PC code base on feedback from utility users.

> <u>Develop a true Windows format.</u> The current version of SAFER-PC consists of DOS executable modules that are called from a Windows template. This version was developed using Windows version 3.1 and has experienced problems operating under later versions. It is proposed to develop a more rigorous interface that can operate under current versions of Windows95, Windows98, and WindowsNT.
>
> <u>Create better graphics plotting and analysis output</u> that allows the user to easily view and print out selected plots and graphs as well as view and edit complete text files of analysis output.
>
> <u>Add cut and paste features for graphs and plots</u> to facilitate inclusion in other documents and to provide for electronic transfer of results.
>
> <u>Develop editing capability for accumulated input</u>. This should allow users to view and correct all the input data without having to refer back to the numerous input screens used to build the file. Currently, many users revert back to the DOS files to do this.
>
> <u>Improve the probability input and analysis methodology.</u> The material property data is currently curve fitted which can lead to some very low estimates of Kic and other input. When the Monte Carlo analysis uses these lower bound values too frequently, it can result in an analysis that is artificially conservative. Even new rotors which have been analyzed can have too high a probability of failure. It is proposed that the user be able to adjust the distribution and confidence level of the data based upon experience, material testing of samples removed from a specific rotor, or manufacturer's test data. Data should

be fit in a standard distribution format with the analysis capable of controlling the standard deviation and confidence. This option should be tested and benchmarked so that a rotor in good condition would experience a 10^{-4} failure probability as reported in the "Bush" data.

Revisit boresonic data clustering and plotting routines. The original clustering routine has remained nearly intact from the mainframe version of SAFER developed in the early 1980s. There has also never been a plotting routine for either the raw boresonic data or subsequent clustered indications. Technology today should allow for algorithms to condition data from various test systems. This would require knowledge of how each inspection vendor handles their data, but there are relatively few systems commercially available and their approach to NDE data is fairly well fixed and understood. Analysis and plotting modules for each type of system should be incorporated into SAFER-PC.

In addition to the above list the overall user friendliness of the code needs improvement. The current interface can be unwieldy and is not easily understood by reviewing the documentation. Expanding the user base for SAFER-PC will be difficult if improvements are not made.

Summary

Utility engineers can use SAFER-PC, an enhanced personal computer version of the original mainframe program, to make independent, unbiased assessments of the remaining life of turbine or generator rotors. These assessments can supplement or replace equipment manufacturers' recommendations.

Improvements to the code will facilitate ease of use and provide for a more accurate remaining life assessment. Enhancements to the interface should also expand the user base for SAFER-PC. The proposed improvements are scheduled to be performed in 2000 subject to funding and workplan priorities as set by the appropriate steering committees.

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