Advancements in Transient Thermal Stress Analysis Technology for Application in Reactor Transient Fatigue Monitoring

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INTRODUCTION

Direct calculation of fatigue usage in nuclear power plant components, based on reactor process parameter instrumentation, has been demonstrated [EPRI, 1988, EPRI, 1989]. In the initial project at San Onofre Unit 2, fatigue usage was predicted for the charging nozzles on the reactor coolant piping [Kuo, Tang and Riccardella, 1986]. Predicted fatigue usage was considerably less than that based on design transients. For the BWR pilot project at Quad Cities Unit 1, the feedwater nozzle safe ends and vessel nozzles were monitored.

In both applications, the EPRI–sponsored **FatiguePro** fatigue monitoring system was used. The software, designed for utilization on a personal computer, employs the methodology illustrated in Figure 1.

1) Plant process data, stored on magnetic media, or downloaded directly from the plant process computer, are processed.

2) Through logical evaluation of the data and application of various transfer functions, local thermal conditions and applied loadings are predicted at the monitored locations.

3) Local stresses are determined using stress transfer matrices and a unique Green's Function thermal stress calculation algorithm. The Green's Function is defined as the local stress response per unit change in the local fluid temperature. A typical example is shown in Figure 2.

4) Conservative assumptions are made to combine principle stresses to determine local peak stress intensity response.

5) An ASME Code fatigue analysis is conducted based on the accumulated stress peaks and valleys for all transients which have occurred in the plant. The overall ordered range method (racetrack counting) is used to determine a stress range spectrum [Fuchs and Stephens, 1980].

The transient analysis is typically conducted for one hour time intervals based on an integration time step of 5 to 10 seconds. With **FatiguePro**, the input data may also be created with a spreadsheet program, such that a personal computer can be used as an engineering tool for transient stress evaluations.

Thus, the major task in developing a plant–specific fatigue monitoring system is that of developing the algorithms which will best simulate stresses at the fatigue sensitive locations. Existing plant instrument response must be properly interpreted to conservatively predict local stresses for all operating conditions. An accurate simulation is the key to performing a realistic fatigue analysis, since actual thermal stresses are much less severe than those determined in component stress reports.

This paper presents several examples to demonstrate how actual plant data may be evaluated to perform realistic local thermal stress and fatigue analysis.

TRANSIENT ANALYSIS APPROACH

As previously described [Kuo, Tang, and Riccardella, 1986], the transient stress simulation is based on interpretation of plant instrumentation. The total local thermal stress intensity is determined from:

$$\sigma = \sigma_{\mathrm{n}} + \sigma_{\mathrm{p}} + \sigma_{\mathrm{t}}$$

where:

σ = total stress intensity
σ_{n} = stress intensity due to constant loads (which can actually be neglected for a fatigue analysis)
σ_{p} = stress intensity which can be related directly to a plant instrument
σ_{t} = stress intensity which must be determined from a logical or transfer function algorithm.

In actual practice, conservative assumptions are made to convert the combined radial, axial and hoop stresses into stress intensity. In addition, signs of combined loadings must be carefully evaluated to assure that the maximum stress range and critical location is evaluated for the critical component.

TRANSIENT THERMAL STRESS RESPONSE

Several algorithms have been proposed for determining transient thermal stress response due to an arbitrary temperature response at the boundary of a monitored component [Kuo, Tang, and Riccardella, 1986; Bimont and Aufort, 1987]. In **FatiguePro**, thermal stresses are based on finite element analysis to determine the stress response to a unit step in temperature at the surface of the component. The resulting stress response, termed the Green's Function, is integrated over time to determine the stress response, σ, due to an arbitrary temperature time history:

$$\sigma = \int_0^t G(t-\tau)\ \frac{\partial}{\partial\tau}\,\phi(\tau)\ d\tau$$

where:

$G(t)$ = Green's Function
$\phi(\tau)$ = local temperature at the monitored location
τ = time

This Green's Function must be based on conservative material properties and boundary heat transfer coefficients.

APPLICATION TO MULTIPLE BOUNDARY CONDITIONS

Many critically stressed components are affected by several thermal boundary conditions. In the following, application of the Green's Function technology will be extended to several more complicated situations.

1) Component Primarily Affected By One Fluid

A typical situation is that of a reactor vessel nozzle safe end. The transient stresses are primarily due to nozzle fluid transients, and the temperature response of the reactor vessel is very slow so as to produce only quasi–steady stresses at the nozzle safe end. In this case, the Green's Function may be based on the difference between the nozzle fluid temperature and the reactor temperature. Care must be taken in using this approach with bimetallic–components. For example, the thermal stresses due to any cladding must also be included in the component model.

2) Component Affected By More Than One Fluid

For this situation, the thermal stresses at the location of interest are determined as the sum of the Green's Function responses due to each of the fluids. A reference temperature can be chosen for the zero stress condition. For typical components, this is taken as the ambient temperature. With this approach, the stresses which develop in bimetallic components are inherently included in the Green's Functions.

3) Components Affected By Multiple Heat Transfer Coefficient Boundary Conditions

In the above applications, constant heat transfer coefficients were assumed. Handling varying heat transfer coefficients at the boundary of the component is very difficult, since the Green's Function is determined based on a linear thermal stress analysis. However, the multiple fluid approach described above may be extended to adequately simulate multiple heat transfer conditions.

Consider the case of a pressurizer wall which is affected by either local steam conditions (with a relatively low heat transfer coefficient) or by pressurizer spray (with a relatively high heat transfer coefficient). Both fluids are assumed to concurrently act on the surface. During conditions of spray impingement, the spray Green's Function is applied at the local spray temperature, and the steam Green's Function is applied at the zero stress temperature, chosen as ambient. When the spray is turned off, the spray Green's Function is applied at ambient temperature, while the steam Green's Function is applied at the local saturation temperature. The resulting summation of the predicted stress responses properly accounts for the heat transfer coefficient change.

ACCOUNTING FOR REMOTE SENSOR DATA

In many cases, the local temperatures at a nozzle must be determined based on a local measurement which is some distance upstream of the monitored location. Due to thermal inertia of the piping, and the distance between the sensor and the monitored location, there will be a time delay and a thermal response lag between the sensor and the monitored location.

A typical situation occurs in the charging nozzles of a PWR. As shown in Figure 3, the fluid temperature is measured at the outlet of the regenerative heat exchanger. Piping lengths are such that the fluid transit time between the instrument and the nozzle differ for the two nozzles. To account for this, a pseudo–Green's Function approach is used to determine the local thermal response at the charging nozzles, as affected by the fluid thermal conditions at the regenerative heat exchanger outlet. A thermal–hydraulic model was used to predict the temperature response at the changing nozzle due to a step change at the sensor, for both the long and short charging line, as shown in Figure 4. These Green's Functions are treated mathematically the same as the thermal stress Green's Functions to determine local fluid response at the charging nozzles. The predicted local temperature is then used with a stress Green's Function to predict local stresses.

CONCLUSIONS

This paper has demonstrated several applications which may be used in fatigue monitoring systems to conservatively and realistically determine thermal stress response of fatigue sensitive components. It has been shown that the Green's Function approach may be extended to handle multiple fluids and heat transfer coefficients, and the approach may by modified to predict fluid transit times and effects due to thermal inertia. Approaches such as these are very useful in producing stress analysis simulators and for transient fatigue monitoring.

ACKNOWLEDGEMENTS

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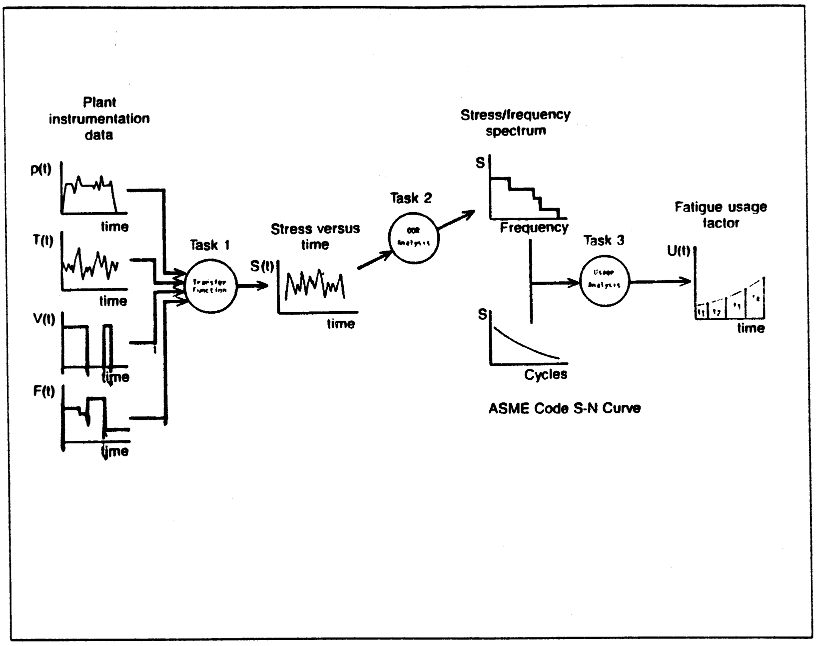

Figure 1. Schematic of **FatiguePro** Fatigue Usage Monitoring Methodology

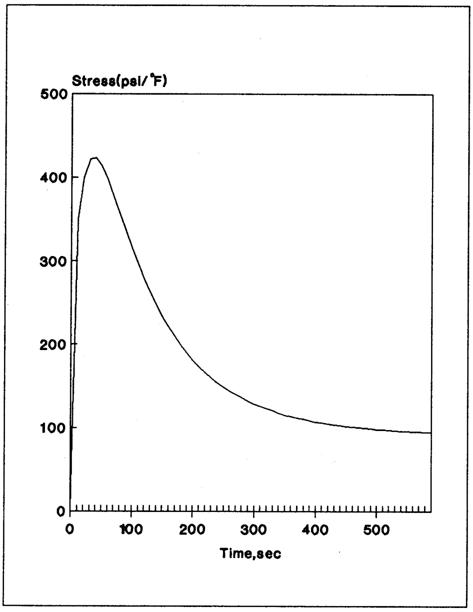

Figure 2. Typical Stress Green's Function
(Response to Step Temperature Change)

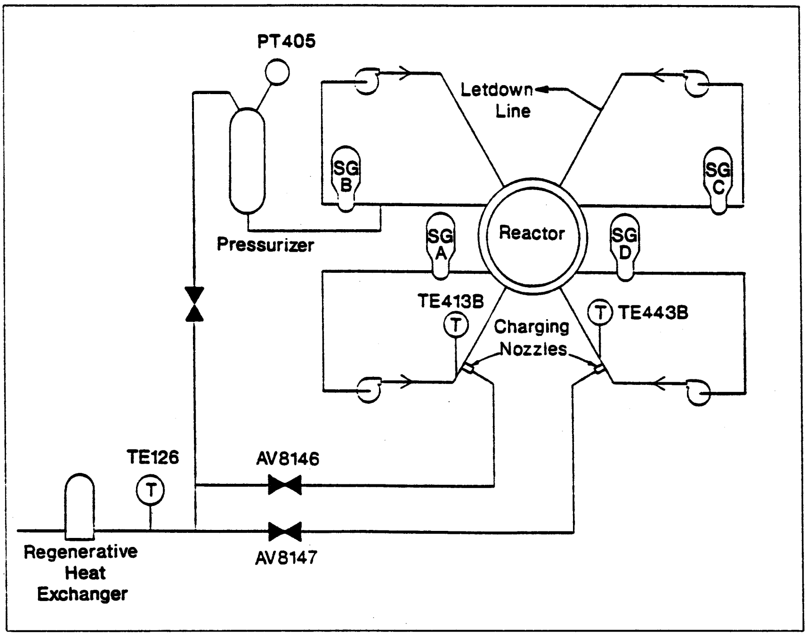

Figure 3. Diagram Showing Location of TE 126 to Charging Nozzles

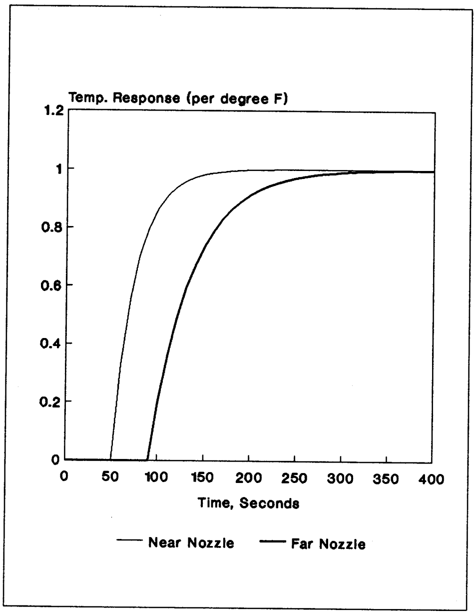

Figure 4. Transient Delay Transfer Function