Automatic Fatigue Monitoring Based On Real Loads

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ABSTRACT

The ageing management of power plants is nowadays a main issue for all nuclear industry actors: states, regulatory agencies, operators, designers or suppliers. Consequently, many operators have to deal with demanding security requirements to ensure the operation of power plants. Regarding fatigue assessment of nuclear components, stringent safety standards are synonymous with new parameters to take into account in the fatigue analysis process, for instance: new design of fatigue curves, consideration of environmental parameters or stratification effects. In this context AREVA developed within the integral approach AREVA Fatigue Concept (AFC) new tools and methods to live up to operators’ expectations. Based on measured thermal loads, the Fast Fatigue Evaluation (FFE) process allows for highly-automated and reliable data processing to evaluate time-dependant cumulative usage factors of mechanical components. Calculation and management of results are performed with the software FAMOSi, thus impact of operating cycles on components in terms of stress but also with regard of fatigue can be taken into account to plan an optimized decision related to the plant operation or maintenance activities.

This paper mainly describes the calculation methodology used to perform a Fast Fatigue Evaluation, but also application examples with relevant results to point out the benefits of this method to the ageing management of mechanical parts.

1 INTRODUCTION

Within the continuously accompanying licensing process for nuclear power plants until the end of their operational lifetime, the ageing and lifetime management plays a key role. Here, one of the main tasks is to assure structural integrity of the systems’ components. In this context, AREVA developed within the integral approach AREVA Fatigue Concept (AFC) [1] new tools and methods to live up to operators’ expectations. In light of the tightening fatigue codes and standards, the urge is clearly present that, in order to still be able to comply with these new boundaries, margins which are still embedded within most of the fatigue analyses in use, have to be reduced. Moreover, thermal conditions and chemical composition of the fluid inside the piping system influence the allowable fatigue levels, which have come under extensive review due to the consideration of environmentally assisted fatigue (EAF). Therefore, for highly loaded components, some new and improved stress and fatigue evaluation methods, not overly conservative, are needed to meet the increasingly stringent allowable fatigue levels. The Fast Fatigue Evaluation (FFE) is a new AREVA solution based on processing measured thermal loads to evaluate time-dependant cumulative usage factors of mechanical components.
2 FAST FATIGUE EVALUATION FOR THERMAL APPROACH

2.1 Definition of the inverse problem

The determination of the time-history of loads and the resulting local stresses are the basis of the method. On a measuring section, close to the fatigue relevant location, the monitoring system FAMOSi measures the temperature at the outside surface of the pipe. First of all the interpretation of this temperature has to be explained.

The stratification effects will not be considered here and the application of the method will be restricted to plug flow events for, a homogenous isotropic solid. In this case, the temperature evolution written in a cylindrical coordinate system is independent of the circumferential direction \( T = f(r, z, t) \). Moreover the measuring section is taken on a pipe relatively far from geometrical discontinuities so that \( T(z - \delta) = T(z + \delta) \). That means we locally consider that the temperature in the observed section can be written as \( T = f(r, t) \). This involves the following equation of heat conduction [2]:

\[
\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} = \frac{\rho c}{\lambda} \frac{\partial T}{\partial t}
\]

(1)

“\( \lambda \)” is the thermal conductivity of the solid [W/(m·K)]

“\( \rho \)” is the density of the solid [kg/m³]

“\( c \)” is the specific heat of the solid [J/(kg·K)]

This equation handles the thermal evolution inside the thickness of the pipe. The solution of the equation depends on the applied boundary conditions. As the varying load is the medium temperature flowing throughout the component, the heat transfer between the fluid and the inner surface is governed by a Newton’s law of cooling as shown in the Eq. (2) below.

\[
\lambda \frac{\partial T}{\partial r} \bigg|_{r=r_i} = h(T - T_{\text{in}})
\]

(2)

“\( h \)” is the heat transfer coefficient [W/(m²·K)]

![Figure 1: Different way to obtain the inner wall temperature](image)
All the difficulty to apply this equation during unsteady fluid temperature states is due to the determination of the heat transfer coefficient $h$. Indeed, this parameter depends on the velocity, the thermo-hydraulics conditions and the geometry of the surface (see Figure 1). The time-dependent knowledge of all these parameters with sufficient accuracy is hardly compatible with a fast determination of the real loads. To solve this problem, the inverse philosophy was developed to calculate the stresses in the structure. Indeed to perform a structural analysis, the knowledge of the temperature distribution throughout the wall is sufficient. The FFE method is based on the time history determination of the inner wall temperature by solving the inverse problem of conduction of heat.

2.2 Solving the inverse problem

Solving the inverse conduction equation of heat is done by application of potential functions (unit transients). A unit transient is applied at the inner surface of the pipe (boundary condition), the equation of conduction of heat is solved, the resulting time-history temperature at the outer wall is obtained. The resolution of the equation of heat can be done by means of an analytical method or with the help of the finite element FE program (ANSYS®). In that case a 2-dimensional model of the section of the pipe is generated (see Figure 2). A benefit of this last choice is the opportunity to integrate the thermal influences of the thermocouple installation at the outer surface of the pipe in the solution.

Figure 2: FE calculation of the temperature response at the outside of the pipe

The determined temperature response calculated in the thermocouple (outer wall) will be considered as a reference. Its evolution is characteristic of the applied unit transient at the inside surface of the pipe (characterized with a temperature rate of changes and a thermal amplitude $\Delta T_{\text{ref}}$). Thus the FAMOSi measured outside temperature will be scanned step by step (typically every second). The temperature difference at the outer wall between two time steps is compared with the simulated outer wall temperature. The factor resulting from this comparison is due to linear properties also available at the inner side of the structure. So that, step by step the inside temperature of the pipe can be restituted. A computation algorithm of this process was developed. A preliminary work consists to calculate, for the different observed piping sections, the thermal references. These last ones are depending on the material, pipe thickness and measurement thermocouple. After this pre-processing work, the computation of the inner wall determination is totally automated.
2.3 Measured temperatures close to a spray line flange

On the pipe elbow between the flange and a spray nozzle of the pressurizer, a monitoring system composed of two thermocouples is installed close to the flange at the outside surface of the pipe and records the temperatures on upper (12h) and lower (6h) locations.

Figure 3: Measured temperatures close to the flange. One year operating cycle, zoom on start up and shut down

The operating cycle presented in this paper is plotted on Figure 3. During the shut down of the power plant a number of high temperature cycles can be seen. Such changes could be significant in the fatigue determination. The measured data can be imported in the software FAMOSi for a first plausibility check. This process is partially automatized, measured data are scanned, higher temperature ranges or gradients are found and can be corrected with linear interpolation or manual corrections. Data are read step-by-step and the temperature difference between two load steps is compared to the response to a reference unit transient calculated in the post-processing phase. The scaling factor between measured and reference temperature gives the temperature at the inner surface of the pipe. Results are presented in Figure 4.

Figure 4: Calculation of inner temperature, zoom on shut down
The process is fast and stable (few oscillations and no parameters to be optimized), on the other hand this method is limited by the thickness of the pipe where measurement tape is installed. For majority of pipes [10mm, 40mm] where installation is performed, an accuracy of the method higher than 95% is expected.

2.4 Thermal load: verification of the inner temperature

A verification of the results can be performed on a few load steps of previously calculated temperature. Calculated temperature with FFE (inner temperature) are used in the finite element software ANSYS®. The conduction problem is solved, then the temperature calculated at the outer surface of pipe/model and measured temperature can be compared.

3 FAST FATIGUE EVALUATION FOR STRESS DETERMINATION

3.1 Pre-processing for stress determination

The unit transient method is also applied to calculate thermal stress for components with complex geometry where no analytical solution is possible. The component should have locally a linear character: no material differences, or contact connections close to observed location. A finite element model of the component is built for initialization of the fast fatigue method. But instead of applying thermal transients (design transients or catalogue transients) as a boundary condition, a unit transient (impulse with reference amplitude and gradient) is applied. Resulting thermal stresses in 6-directions are calculated. Fatigue relevant locations are determined on high thermal stress locations or welds. At these locations time-dependent stress results are saved in the FAMOSi data base.

Figure 5: Thermal unit transient is applied (left) as boundary condition, resulting stress is calculated (right)

The saved stress references will be scaled according to the previously calculated inner temperature load with a frequency up to 1Hz, single contributions are summed-up time dependently in order to build the thermal stress history at the observed locations. Verification is possible since the calculated load (inner temperature) can be input in a finite element software (ANSYS®). Because of long processing time with the three-dimensional FE model, verification is just done for, a few load steps transients. The temperature field in the structure
is calculated at every node, then the calculated temperatures on nodes are read in the structural FE model. Resulting stresses are calculated and can be compared with results of FFE FAMOSi. Comparison of results for several geometries and situations shows that deviation between both methods is typically lower than 3%.

3.2 Stress determination

The temperature calculated at the inner surface is applied as a thermal load in FAMOSi for stress determination. In local temperature measurement approach, thermocouple sensors are placed close to the relevant fatigue locations (for instance spray lines, feedwater nozzles, surge line, flange connections, heat regenerative exchangers). If instrumentation is not directly installed close to the analyzed component, some correction factors can be applied. The calculated temperature is scanned with a frequency up to 1Hz and decomposed into unit transients. The stress contribution of every unit transient is superposed to calculate total stresses and linearized stresses. Results are saved in a data-base and can be easily plotted or used for further data processing. The data base was structured to manipulate large amounts of data (several power plants with full monitoring locations and operating cycles) thus the visualization of channels is not impacted by the amount of recorded data. For instance stress determination (6 stress components, 6 linearised components and a temperature channel) for a whole operating cycle at a weld seam location can be performed within few minutes on standard computers. If pressure or piping loads variation has an influence on the stress at the observed location, mechanical stress can be added to the thermal stress in the software. This operation is particularly relevant at weld connections.

4 FATIGUE DETERMINATION

4.1 Consideration of environmental factors

During the last years, laboratory scale experiments worldwide showed that the environment laboratory scale of light water reactors does have a significant impact on the material that might not be covered completely by the margins (not safety factors) applied to the “in air” curves. Lives of test specimens obtained from experiments in LWR environment can be much shorter than those obtained from the corresponding test in air. A factorial approach based on penalty factors $F_{en}$ was proposed in [3] and is actually implemented in the Regulatory Guide [5] and the ASME Code Case [6] or EPRI Guideline [7]. The usual way of considering environmental effects in the analysis is the application of penalty factors $F_{en}$ representing the achieved life cycles “in air” at room temperature $N_{RT,air}$ and “in medium” at operational temperature $N_{T,water}$ as proposed in Eq. (3).

$$F_{en} = \left( \frac{N_{RT,air}}{N_{T,water}} \right) \text{ with } F_{en} \geq 1$$ (3)

The usage factor considering environmental effects is determined by application of the linear damage accumulation rule (Miner’s rule) according to Eq. (4).

$$U_n = \sum \frac{n_i}{N_{i,RT,air}} \cdot F_{\sigma_1} + \sum \frac{n_i}{N_{i,RT,air}} \cdot F_{\sigma_2} + \ldots + \sum \frac{n_i}{N_{i,RT,air}} \cdot F_{\sigma_k}$$ (4)

$n_i =$ Number of really occurring operational cycles


\( N_i = \) Number of allowable cycles according to the design curve

\( F_{en,i} = \) Fatigue penalty factor

Calculation of \( F_{en} \) factors is performed in this example according to [3]. For every cycle the value of \( F_{en,i} \) depending for instance of the strain rate \( \varepsilon \), sulfur content \( S \), temperature \( T \), or dissolved oxygen (DO) level is calculated (see Figure 6 for comparison with fatigue results with air curve).

### 4.2 Cycle counting and fatigue evaluation

Cycle counting is the prerequisite for any fatigue or service durability assessment method dealing with arbitrary operational load sequences. Consequently, an appropriate cycle counting algorithm is required. The superposition of transients according to the design code (ASME Code, NB 3222.4 [4]) is based on the peaks and valleys method. The largest stress ranges are usually determined from “outer combinations” (e.g. load steps across different transients respectively events). The associated frequency of occurrence results from the actual number of cycles of the participating two events with the smaller number of cycles. This event provides the associated contribution to the partial usage factor \( U_i \). The summing up of all partial usage factors according to Miner’s rule delivers the accumulated damage (usage factor \( U \)) or cumulated usage factor CUF. Additionally, a counting of sub cycles within the events should be carried out according to the rain-flow cycle-counting method e.g. [8] although it is not explicitly addressed by the design code [4]. This is standard practice in the framework of the AFC.

In Figure 6, time-dependant cumulative usage factor calculated within air and under consideration of environmental effects can be seen. Based on time-dependent consideration of usage factor, better relations between operation modes (temperature evolution in blue) and structural analysis of components can be performed. Moreover prognostics on life time of components can be done and, if needed, correction on operating modes easily applied.

![Figure 6: Time-dependent cumulative usage factor with and without consideration of environmental factors](image-url)
5 CONCLUSION

The AREVA integrated and sustainable concept of fatigue design expresses the importance of design against fatigue in nuclear power plants. Actually, new plants with scheduled operating periods of 60 years, lifetime extension, the modification of the code based approaches and the improvement of operational availability are driving forces in this process. The Fast Fatigue Evaluation was developed to complete the AFC model and answer operator’s expectations: deliver an accurate fatigue analysis through highly automatised processing of measured data. Based on a flange example, FFE process with detailed consideration of environmental effects according to NUREG/CR-6909 ANL 06/08 [3] (calculated penalty factor $F_{en}=2$) was shown. Moreover the integrated solution FAMOSi ensures the effective data processing from measurement to fatigue data calculation and offers the user an easy to use interface to nuclear power plants loading data. Based on a modular development, the FAMOSi software can be easily updated according to code cases evolution or the further development of a stratification module. Thus, the integrated fatigue approach makes a significant contribution to the monitoring of safety margins, the operational availability and the protection of investment.

REFERENCES


