Concept of a New Method for Fatigue Monitoring of Nuclear Power Plant Components

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ABSTRACT

Fatigue is one of the well-understood aging mechanisms affecting mechanical components in many industrial facilities including nuclear power plants. Operational experience of nuclear power plants worldwide to date confirmed adequate design of safety related components against fatigue. In some cases however, for example when the plant life extension is envisioned, it may be very useful to monitor the remaining fatigue life of safety related components.

Nuclear power plants components are classified into safety classes regarding their importance in mitigating the consequences of hypothetic accidents. Service life of components subjected to fatigue loading can be estimated with Usage Factor $u^k$. A concept of the new method aiming both at monitoring the current state of the component and predicting its remaining lifetime in the life-extension conditions is presented. The method is based on determination of partial Usage Factor of components in which operating transients will be considered and compared to design transients.

1 INTRODUCTION

The pressure boundary components of nuclear power plants are designed, manufactured and erected according to standards (e.g. ASME Section III [1]). The issues of prediction and extension of the safe life time have attracted considerable attention in the power generation industry. One of the most critical factors for plant life extension is fatigue. Several investigators (e.g. [2], [3]) have contributed to the various aspects of life prediction methodology. The integrity of important components is essential for operational safety, reliability and economic plant operation.

In the design, the life of a plant is estimated conservatively. Because of the conservatism in the design and the development in monitoring, understanding and predicting the degradation mechanisms, the actual lives of these plants may exceed the original design value. The sustained interest in the area of remaining life prediction arises from the advantages of extending the component operation life beyond the original design life and avoid costly outages and last but not least, from the safety considerations.

The major factors that affect the fatigue life of power plant components are the fluctuations of temperatures, pressures and flow rates of the process fluid. During the design
phase, the effects of fatigue are estimated and restricted conservatively in accordance with the ASME Boiler and Pressure Vessel Code [1]. End-of-life fatigue usage factors are calculated assuming a set of conservative design transients to ensure that plant components do not exceed a cumulative fatigue usage factor of unity throughout their design life. Real life plant operating cycles, however, may be quite different from the transients assumed in the design. In most of the cases, the plant operation is conservatively restricted simply by the number of design transients.

It has been demonstrated by several researchers (e. g. [2], [3]) that the implicit margin can be estimated to extend the useful life of plant components using on-line fatigue monitoring systems. Information about accumulation of fatigue helps in assessing the structural degradation of the components, defining the in-service inspection and maintenance schedule and supporting a future life extension program of a power plant based both on design assumptions and observation or operational history.

One of the most important steps in on-line fatigue monitoring is relating the information of plant operating transients to the temperature/stress responses in the structure. The technique widely used is based on Green’s function, which can generally be applied to the linear analysis [3]. Another way to determine temperature/stress response in the structure is using of finite element analysis, which is very general but may turn out to be very resource intensive. Therefore it is reasonable to develop a tool for on-line fatigue monitoring which will optimally combine advantages of presently used methods for determination of remaining life of the nuclear power plant. These advantages are used to set up a user-friendly monitoring system. The concept for this system is general and is presented in this paper. The application of the concept will be done for the determination of fatigue usage and its remaining life of selected component of the Krško Nuclear Power Plant (KNPP), which supports this work together with Slovenian Research Agency.

2 FATIGUE MONITORING

A fatigue monitoring system is in general a computer tool that allows the continuous register of selected components conditions, by on-line data acquisition, and the continuous update of their fatigue damage estimates. Widely used method for determination of fatigue damage is based on fatigue usage factor. Therefore an appropriate tool should be developed which can transform plant instrument data to the fatigue usage factor of the component. The presented concept of fatigue monitoring system will be implemented for selected components in KNPP, which has been in operation for more than twenty years. Because of the conservative procedures in design of components, regular inspections in KNPP show good condition of piping of safety class I. Fatigue analyses done in the design phase predicted that operating service life of piping of safety class I is at least 40 years. The proposed concept may contribute to the eventual extension of operating service of KNPP beyond 40 years design lifetime.

2.1 Fatigue usage factor

The inclusion of fatigue as a potential failure mechanism in ASME section III was intended to increase the reliability of reactor vessel and other important components performance. There is ample operational experience demonstrating that the NB Section III S-N fatigue approach has provided a safe design against failure. This approach to fatigue evaluation is based on fatigue curves of stress versus number of cycles (designated as S-N curves). The intent of Section III was for fatigue analysis to be used, not so much to quantitatively predict fatigue life but to demonstrate that the fatigue usage factor for the anticipated life of the vessel was less than 1.0 for normal operating transients. The major
conservatism is that actual plant operational transients have less severity and fewer cycles than design assumptions; therefore, the Section III analysis procedures are conservative.

The basis of the fatigue assessment procedure (Figure 1) is that fatigue damage, caused by cyclic loading, is cumulative and that the summation of this damage during component life shall not exceed 1.0.

Fatigue damage is estimated by the usage factor. A partial usage factor is obtained by the ratio $n_i / N_i$. The term $N_i$ is the number of allowable cycles at a given stress level obtained from the appropriate fatigue curve, whereas term $n_i$ is the number of cycles to be applied during the operating life of the component. When there are multiple operating conditions, each operating condition generates a partial usage factor. A cumulative usage factor (CUF), known as the Palmgren-Miner linear damage relationship, is obtained by summing the partial usage factors:

$$\sum_{i}^{P} \frac{n_i}{N_i}$$

where $P$ is number of different cyclic operating (loading) conditions. Fatigue damage is quantified in terms of alternating stress intensity ($S_a$), which is one-half the difference between the maximum and minimum cyclic (Tresca) stresses at the point of interest in the component. Alternating stresses are determined on a cross-transient (operating-cycle) basis to maximize their value – that is, the “cross-transient” procedure requires the range be based on the maximum stress difference minus the minimum stress difference of all the transients.
Generally, the stress versus time history is irregular in nature. Rainflow cycle counting algorithm [4] has proved to be superior to other cycle counting methods for analyzing irregular stress history. The apparent reason for the superiority of the rainflow cycle counting algorithm is that it combines load reversals in a manner that defines a cycle as a closed hysteresis loop. Each closed hysteresis loop has a strain range and mean stress associated with it that can be compared with the constant amplitude fatigue data in order to compute the fatigue usage factor. In this method, the cycles are defined in such manner that small stress excursions are considered as temporary interruptions of larger stress excursions. It matches the highest peak and deepest valley, in descending order, until all peaks and valleys are paired. Several algorithms (e.g. Downing and Socie [4]) are available for counting cycles following the rainflow technique. From the stress cycles, the fatigue usage factor is computed using the material fatigue curve.

2.2 Fatigue monitoring system

Classical approach of monitoring fatigue life of important components with regard to ASME in nuclear power plants compares the number of operating transients with design transients. As long as the number of operating transients is within the design assumptions, the safe operating is assured with respect to the fatigue. Such approach tends to overestimate the usage of the components and is therefore conservative. Overestimated fatigue usage factors may, if properly re-evaluated, contribute to the extension of service life of nuclear power plant components (from 40 to 60 years). Based on this method a reliable assessment of components real condition should be done, wherefore operating transients in components must be known. Fatigue monitoring will be performed mainly on safety related components of nuclear power plant.

Operation of a nuclear power plant causes temperature, pressure and flow fluctuations in the reactor coolant, which might be reflected in fatigue degradation. The operating transients in KNPP are recorded by a data recording system at time intervals of 1 min. Recorded data will be filtered because small changes in transient have negligible influence on usage factor. Filtered data of temperature variation, pressure variation and flow variation will be used to compute stresses in the observed component. Transients in the order of 1 min or lower may not be well represented in such data bases. Special attention will be given in later steps of the project.

![Figure 2: Temperature distribution through a wall thickness of a pipe for transient at time t = 1, 10, 100 s and for steady state condition](image)

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Generally fatigue monitoring systems take care of fluctuations in the temperature, pressure and flow parameters. In proposed concept special care will be focused to the thermal transients, which cause time-varying temperature distribution across the wall of the observed component (Figure 2). The variation of temperature through the wall can be captured with analytical expressions [5] for simple geometry (e. g. pipes, head of vessel, pressurizer, steam generator…) and/or with finite element model, whereas the variation through the complicated geometry (e. g. nozzles) can be captured with finite element analysis. Results in Figure 2 show that the temperature gradient at the beginning of the temperature transient is higher then the gradient for steady state condition. This results in a thermal stress distribution across the wall thickness.

The same analysis procedures may be used for pressure and flow transients. Apart from these process parameters, the additional system induced external loads may also contribute to fatigue degradation of components. These external loads usually arise from the piping system. The external loads and bending moments acting on the selected component will be computed by carrying out piping analysis of the system. The resultant stresses will be computed using a 3-D finite element analysis. Through this analysis, a data base will be generated for the selected components for change of process temperature and pressure. This data base will be used in the fatigue monitoring system and these stresses will be superimposed with the stresses due to process parameter fluctuations.

Responses from off-line analysis, done with appropriate analytical and numerical methods, will be used in order to evaluate transfer function for determination of stresses in on-line analysis.

3 CONCLUSION

The concept for a general on-line fatigue monitoring is presented. It is based on determination of the fatigue usage factor and will optimally combine advantages of numerical methods and analytical expressions for determination of fatigue damage and remaining life of the nuclear power plant. During off-line phases a thermal model and a thermoelastic model will be used for observed components to evaluate the response in order to use them on-line to evaluate transfer function for thermoelastic stresses for operating transients. The concept will be applied for determination of fatigue usage of observed component and for determination of its remaining life in Krško Nuclear Power Plant, which supports work together with Slovenian Research Agency.

REFERENCES


