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Implementation of finite element based fatigue monitoring system at Heavy Water Plant Kota

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Abstract

A finite element based fatigue monitoring system has been developed for on-line monitoring of fatigue degradation of components used in various plants. The system can take care of the fluctuations of the process fluid temperature, pressure and flow rate. This can also account for the system induced loads such as axial forces and bending moments. The system converts the plant transients to temperature/stress responses using finite element method, computes the fatigue usage factor and updates the information continuously. This system is capable of analysing several components of a plant using a P.C. 486. As a part of life extension programme of Heavy Water Plant Kota, this system has been installed for monitoring fatigue degradation of important components. This system is successfully under operation since mid 1996.

1. Introduction

Recently, the issue of remaining life prediction has attracted considerable attention in the power generation industry. Several investigators, e.g. Bimont and Aufort (1987), Saxena et al. (1988), Deardorff and Kuo (1989), Liaw et al. (1989), Mukhopadhyay et al. (1993, 1994a,b), Bartonicek et al. (1995), Maekawa et al. (1995), Balley et al. (1995), have contributed to various aspects of life prediction methodology. Integrity of important components is essential for operational safety, reliability and for economical aspects of plant operation. In the design, the life of a plant is estimated. However, because of conservatism in the design the actual lives of these plants are expected to be much more than the estimated value. The sustained interest in the area of remaining life prediction arises from the need to avoid costly outages, safety considerations and the necessity to extend the component operation life beyond the original design life. An on-line fatigue life monitoring scheme has emerged to be a viable methodology to assess actual plant transients, realistic load sequences and number of fatigue cycles. This in turn provides information about the accumulated damage after a specified period.

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A scheme of on-line age monitoring methodology is presented by Mukhopadhyay et al. (1994a). The methodology is explained in Fig. 1. The steps include acquisition of relevant plant transients continuously and converting these transients to temperature/stress responses of the structure. The stress time history is converted to stress frequency spectrum using rainflow cycle counting algorithm as introduced by Socie (1977). Later Downing and Socie (1982), Rychlik (1987), Glinka and Kam (1987) presented various algorithms of rainflow cycle counting technique. In this method the effect of small stress excursions are separated and the relevant dominant cycles capable of producing damage are computed. The fatigue usage factor is evaluated from the computed cycles using material fatigue data.

The important step in on-line fatigue monitoring is the conversion of plant transients to the temperature/stress responses in the structure. The technique generally used in almost all the fatigue monitoring systems is the Green's function technique (GFT). This is a method which transforms the plant transients to temperature/stress responses using a transfer function approach. This transfer function can be generated by analytical method or using numerical methods like the finite element method (FEM), and used as a data base. The advantage of this approach is that the Green's function can be generated for complex structural components adapting detailed modelling of the structure using FEM. The various stress raising effects, e.g. interface of a nozzle with a shell, tee junction, etc. can be incorporated using 3-D model of the geometry. Another advantage of this approach is that the computation time is very less. However, the GFT has some limitations. Strictly the GFT cannot be applied to the nonlinear analysis because of inherent assumptions of linear superposition as have been demonstrated by Chen and Kuo (1989), Mukhopadhyay et al. (1994a), Maekawa et al. (1995). The variation of process flow in the plant gives rise to change in convective heat transfer coefficient which is an input to compute the temperature/stress responses in the structure. The change in convective heat transfer coefficient introduces nonlinearities in the use of GFT. Limited literature is available in treating the effect of variation of process flow on the temperature and stress responses in this method. Maekawa et al. (1995) analysed a thermal cycle considering variation in temperature and flow rate. A difference is observed in the comparison of computed stresses adapting GFT and FEM. The peak and valley values of the stresses, which are major concern for estimation for fatigue usage factor, are fairly coincident in both the methods. The conclusion derived was that the GFT was found to be good for simplified evaluation in obtaining a reasonable time-dependent stress history. Mukhopadhyay et al. (1994a) demonstrated that in the case of discrete variation of process flow the responses can be computed employing Green's functions for different values of heat transfer coefficient separately. The computed stresses agree with the results computed by FEM. However this approach is not applicable to real life situations in plants, where the process flow variation is irregular. The GFT provides information on some predetermined points of the structure. If the number of points are increased, the computation time also increases.

On the other hand a transient FEM analysis can take care of the variations of heat transfer coefficient and can provide whole-field information. The use of FEM is limited due to the large computation time and storage area. However, the availability of fast personal computers, such as P.C. 486 etc., has solved this to a great extent. By using these P.C.s, the FEM can be directly used for on-line fatigue monitoring. We have updated our earlier work on the development of a software for on-line fatigue monitoring (Mukhopadhyay et al. 1994a,b) by implementing finite element modules for the computation of temperature/stress, instead of using the GFT.

Presently there are many commercial softwares available which can perform thermoelastic stress analysis based on FEM. Many of them have also a module for calculation of fatigue usage factors. However the computation time would be much more in these commercial softwares as they are generalised finite element packages. For a fatigue monitoring system (FMS) which has to perform on-line finite element calculations, the need for a

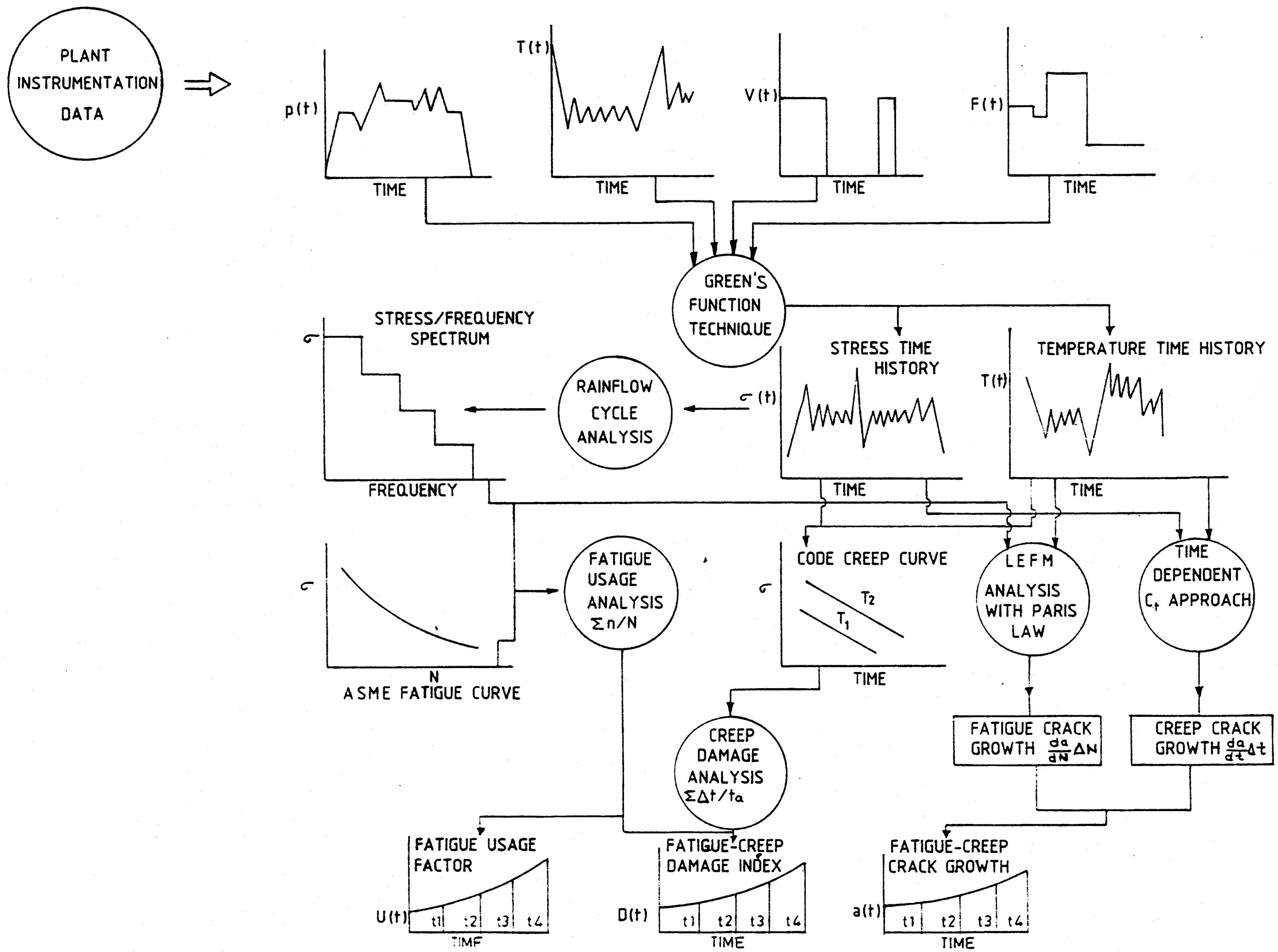

Fig. 1. Different steps in on line age monitoring methodology.

dedicated software is essential. Again the system has to be integrated with a data recording system, which would be difficult with a commercial software. Thus there is a need to develop a finite element based system specifically for fatigue monitoring. The originality of the present system is that it is a dedicated system developed for fatigue monitoring which can convert the plant transients to temperature/stress responses of the structure using FEM. This also can perform the necessary calculations to compute fatigue usage factor based on rainflow cycle counting algorithm. A user's friendly menu driven display of the fatigue related information is another feature of the present system. The system can be integrated to a data recording system and fatigue degradation of several components of a plant can be monitored using a P.C. In this paper the development and implementation of a fatigue monitoring system based on FEM at heavy water plant (HWP) Kota is presented.

2. Life extension programme at HWP Kota

The life of a component is limited by various time dependent failure modes like corrosion, fatigue, creep, fatigue-creep interaction, crack propagation followed by fracture, etc. The estimation of residual life of a component has to take into account of these failure modes. This involves historical review, non-destructive testing, semi-destructive examination and stress analysis. However, fatigue is the most important degradation phenomenon affecting the life of a component.

The heavy water plant, Kota, has completed successful operation for more than 15 years. An assessment of integrity of components in critical areas of HWP Kota has been initiated to estimate the remnant life of the plant. This also involves developments of methodologies required for life extension at a future date. To measure the accumulated fatigue degradation of various components, it has been decided to install a fatigue monitoring system to monitor the fatigue damage of a few selected components. Since the on-line fatigue monitoring system has been installed after 15 years of plant operation, it can also be used to assess the past fatigue usage factor by extrapolating the monitored data. This present work is a part of the on-going programme for life extension of components at HWP Kota. The implementation of a fatigue monitoring system will be described in the following sections.

3. Finite element based fatigue monitoring system

A finite element based 2-D axi-symmetric thermo-elastic computer code has been developed. The code is capable of handling axisymmetric pressure and fluctuating thermal load. The stresses calculated using this code should be superimposed with the stresses due to piping loads, calculated separately. Two diagonally opposite planes are selected. In one plane the bending stresses due to piping loads are maximum tensile and in the other they are maximum compressive. The stresses due to thermo-elastic computation and piping load analysis are superimposed on these two planes. All the nodal points on these two planes are monitored for computation of stress fluctuations. The fatigue cycles on these nodes are evaluated using rainflow cycle counting algorithm and the fatigue damage is estimated using material fatigue data. The code is written in C language. Some special features of the various modules of this system are listed below.

3.1. Temperature transient module

- The formation of element coefficient matrices is done every time to avoid their storage.
- The solution of transient equations are done by using Galerkin's method.
- The active column solver is used to solve the set of equations.
- The temperatures and the thermal load vector at the end of previous day's calculations is stored in a restart file for the computation to proceed for the next day.

3.2. Stress/deformation module

- The decomposed assembled stiffness matrix, after forward elimination is stored as a data base to be used at the beginning of every day's processing.
- For the subsequent solutions, only back substitution is required for a new load vector corresponding to every record.
- The solution scheme is again the active column solver.

3.3. Integration of system induced loads into FMS

Fatigue degradation may be attributed to parameters such as variation in the internal pressure, temperature and flow. Generally fatigue monitoring systems take care of fluctuations in the process parameters. 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 are computed by carrying out piping analysis of the system. The resultant stresses are computed using a 3-D finite element analysis. Through this analysis, a data base has been generated for the selected components for unit change of process temperature and pressure. This data base is used in the FMS and these stresses are superimposed with the stresses due to process parameter fluctuations.

3.4. Screening of transients, data storing and testing of FMS

The plant transients are generally recorded by a data recording system at a particular time interval. This time interval may be small (as for example 0.1–5 s) or larger. This depends on the nature of the plant transients and the performance of the recording system. In some particular situation when the transients are insignificant, the processing of these records are not necessary. In FMS there is a provision of screening the input data received from the plant instrumentation. This helps in reducing the number of records to be processed. The transients are screened based on the severity of the fluctuations and only relevant records are further processed.

In FMS the whole field information for temperature, stresses and fatigue usage factor are stored. The system stores the most severe information for temperature and stresses as a record. After the computation of each day, the system computes the severest temperature and stresses experienced by the component due to the plant transients. The computed values are compared with the stored values. The recorded information is only updated if the structural response due to present fluctuations are more severe than the stored value. In the case of usage factor, the information is always updated after the computation of each day and stored as a record. The time history variations of recorded process flow, computed structural temperature, stresses and usage factor is also stored. The variations for structural responses, are stored at few selected points on the structure. The selection of these points depend on the geometry of the component to be analysed, the flow transients and the boundary conditions. The points are selected in such a manner that they are likely to experience the most severe stress conditions.

This FMS is commissioned in a P.C. 486. The computation speed of the software is tested for an input consisting of five thousand fluid records with 125 relevant significant fluctuations. It is found that the whole procedure, e.g. screening of input data, computation of structural temperature and stress responses, evaluation of stress cycles through rainflow cycle algorithm and determination of usage factor from material fatigue data, takes around 10 min for a single component in a P.C. 486.

3.5. Graphics display module

A user's friendly graphics module is incorporated in FMS for display of relevant results. When initiated this module displays the components selected for fatigue monitoring at the plant site. For a particular component, this shows the geometry, the material properties used and the finite element mesh adapted. The recorded fluid transients are displayed which enable to have an estimate of the operating conditions of the plant. There is a facility for zooming. The time for major shut down and start up of the plant can be approximated from the data logging. The computed stress and temperature histories are also available on display. The calculated rainflow cycles are plotted as a stress frequency spectrum. The usage factor history and the updated damage index in a logarithmic scale can be plotted on screen or paper. The whole field information for structural temperature, stresses and fatigue usage factor are also displayed.

3.6. Data compression algorithm and safety features

The number of stored records for temperature and stress histories will accumulate as the system runs for a longer period of time. A data compression algorithm has been incorporated to restrict the number of history records to a certain storage capacity. The principle of rainflow cycle counting method is adapted in this compression algorithm. Once the number of records exceed the specified storage capacity, the smaller stress or temperature excursions will be overwritten by the larger cycles.

The FMS when triggered, screens the input fluid data, computes the temperature and stress responses, estimates the usage factor, updates all the relevant files, closes all the relevant files and frees the memory space used. The entire scheme was tested after running the programme uninterruptedly for several weeks. However, due to some unforeseen conditions, e.g. power failure or due to human error when the computation is going, it may lead to malfunctioning of the system. An inherent safety feature is introduced in the system to take care of such a situation. A backup directory is created and all the files are stored in the backup directory. When the system is installed, all the relevant files from the backup directory are copied to the present directory. After each day's computation the results are checked, and if all the computations are performed satisfactorily, the updated results are copied to the backup directory. In case of a erroneous computation, (due to some error in input signals etc.) power failure or arbitrary interruptions to the system, the files from the backup directory would be recopied to the present directory. The operation of the system would not be affected although the data for that particular day would be lost.

4. Fatigue monitoring system at HWP Kota

It has been decided to implement this fatigue monitoring system described above, at HWP Kota as a part of the life extension programme. The plant has been already in operation for more than 15 years. The basic objective of this programme is to have an estimate of the degradation effect over the years by extrapolating computed values over a reasonable amount of time period and to help in life extension of the plant. It has been decided to implement the monitoring system in various stages. The selection of components, generation of necessary input data base, implementation of the FMS and its performance is described below.

4.1. Selection of components for fatigue monitoring

The selection of components in a plant requires a thorough understanding of the plant operation and transients. It is neither possible nor economical to monitor the fatigue life of all the components of a plant. Fatigue is monitored for the components which experience the maximum fluctuation of transients. The integrity of the rest of the components is assumed if the usage factor does not exceed the limiting value in the selected components. Generally one P.C. is dedicated to fatigue monitoring of an entire plant. This P.C. collects the process fluctuations from the plant instrumentation, converts them to structural responses in terms of temperature and stresses and computes the fatigue degradation. The required computation time for analysing each component restricts the upper limit of the selected number of components. The computation time also depends on the severity of process fluctuations. Hence, a thorough process dynamics analysis of system is necessary to identify the components which are relevant to monitoring. Nondestructive examination and repairs carried out during fabrication processes and design concession permitted are also considered while selecting the components.

In HWP Kota, the components have been selected based on the chemical processes, plant layout, pressure and flow distribution in different piping systems and availability of existing plant instrumentation. Initially about 25 locations were identified which are expected to experience significant fatigue cycles during normal operation and/or during start up and shut down conditions. These initially selected nozzles are screened based on severity of process fluctuations and availability of plant instrumentation and it has been decided to monitor three components at the first stage of implementation of fatigue monitoring system at HWP Kota. The selected locations are nozzles connecting piping system with the storage vessel/column tower. Due to geometric discontinuity and mixing of process fluids, these nozzles are postulated to be most susceptible to fatigue damage.

4.2. Generation of input data base

The FMS requires the generation of input data base for the selected components. This data base generation depends on the geometrical details of the component, the material properties, the boundary conditions and the piping loads. In HWP Kota, three nozzles are selected for motoring fatigue degradation. The nozzle N01 is a gas outlet nozzle connected to the spherical head of waste stripper column. The nozzle N02 is a gas inlet nozzle connected to the cylindrical column tower. The nozzle N13 is an inlet recirculation nozzle to the cylindrical column tower.

An axisymmetric model of the nozzle is generated for on-line fatigue monitoring. There is a geometric discontinuity at the nozzle vessel junction. The nozzle along with the column tower and reinforcement pad is modelled using eight noded axisymmetric ring elements. The decomposed assembled stiffness matrix, after forward elimination is stored as a data base. The data base for system induced loads is also generated using FEM. The loads acting on the nozzle are considered as input from a piping analysis. The nozzle, vessel and reinforcement pad are modelled using a 3-D finite element mesh with twenty noded brick elements. The effective stresses are computed due to the application of axial force, internal pressure and bending moment. The two diagonally opposite planes experiencing the most severe stresses are selected as the data base.

Due to the restriction in storing the stress and temperature histories of all the nodes of the model, few locations are selected as critical locations where the temperature and stress histories would be stored. These points are selected in the component where the effect of fatigue degradation is expected to be the maximum. In this present case, five such points are selected for each component.

4.3. Implementation of fatigue monitoring system at HWP Kota

The fatigue monitoring system is installed at HWP Kota in mid 1996. It is combined with a disturbance recording system (DRS) developed by Reactor Control Division of Bhabha Atomic Research Center (B.A.R.C.). The system has been described in detail by Chandra et al. (1994). The DRS continuously acquires process parameters associated with the selected components. The signals are converted to relevant engineering units. Every night at 00:00 h, the DRS triggers the fatigue monitoring module. The recorded process data are screened and only significant transients are selected for further computation. After screening, the finite element module computes the resultant temperature and stresses at the nozzle considering the process fluid fluctuations and the induced stresses due to the thermal expansion of the connected piping. After completing the finite element computation, only the relevant peaks and valleys of stresses and corresponding temperatures are stored. The fatigue usage factor is computed using rainflow cycle counting technique and material fatigue data as obtained from ASME Boiler and Pressure Vessel Code (1986). After each day's execution, the computed stresses, temperatures and fatigue usage information are updated using the previous information. The computation is repeated for all the nozzles in sequence.

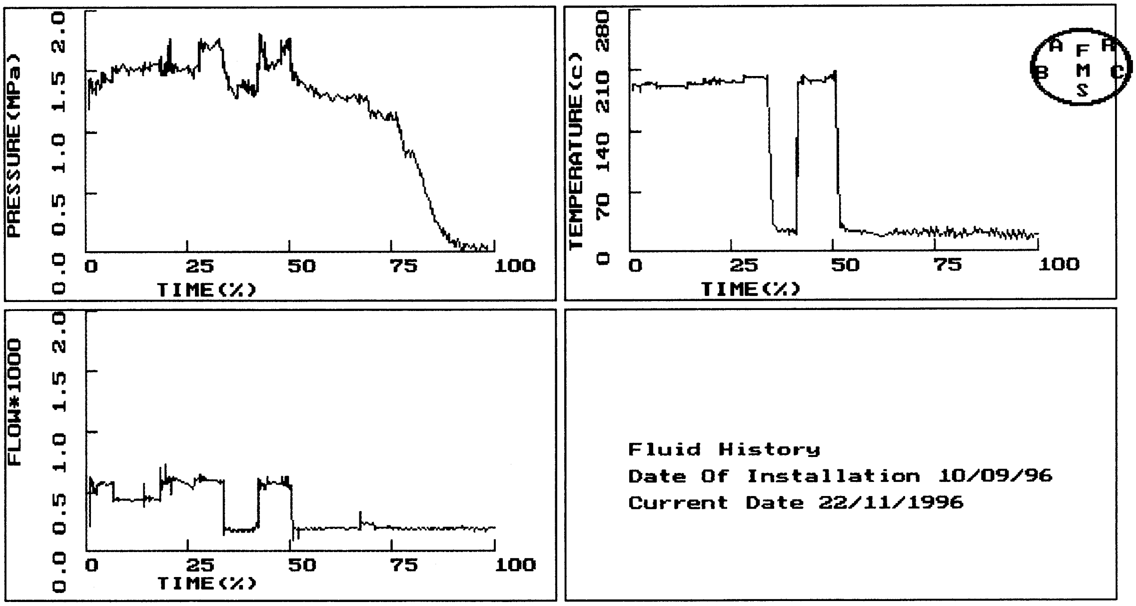

Fig. 2. The variation of process pressure, temperature and flow for nozzle N02.

The FMS records the process pressure, temperature and flow rate for all the three nozzles. A typical recorded process transients after screening the insignificant fluctuations for nozzle N02 is shown in Fig. 2. This figure shows the process transients for nearly two and half a months' period of time. The process fluid temperature varies from 25–210°C. The temperature of the process fluid is around 190–210°C when it is in operation. The recorded history shows that during this period there is one shut down and start up and also a major shut down (Fig. 2). There are few minor fluctuations of temperature while in operation whose contribution to usage factor can only be recognised by employing an on-line fatigue monitoring system. The fluid pressure varies from 0.1 to 1.8 MPa. Generally the fluid pressure varies from 1.2 to 1.8 MPa. During the major shut down the system was depressurised and finally the system pressure is brought to around 0.1 MPa. The minor fluctuations in the pressure is more than that observed in the case of temperature (Fig. 2). The effect of these minor fluctuations are also accounted for by the present FMS. The process flow rate varies from 0 to 32 tons h^{-1}. However in Fig. 2 the derived convective heat transfer coefficient is shown as process flow. The convective heat transfer coefficient is calculated from flow rate using standard correlation. Forced convection is considered when the plant is in operation. For shut down condition (no flow in the nozzle) natural convection heat transfer is assumed. Though the flow rate is zero when the plant is in shut down condition, the calculated heat transfer coefficients show the value due to natural convection in Fig. 2. Like pressure and temperature there are also minor fluctuations in the flow rate. Similar input parameters are also recorded for the other two nozzles.

The recorded fluid transients are processed to calculate the temperature/stress responses on the structure. As has been mentioned in the previous section, the fatigue monitoring module is called at each midnight. This module performs a transient thermal analysis followed by a thermo-elastic stress analysis using FEM. Whole-field information is available about the temperature and stresses on the structure. As the computations are repeated each day, temperature and stress histories are generated. The histories of a few selected critical points of the structure are stored. Here the variation of the computed temperature and

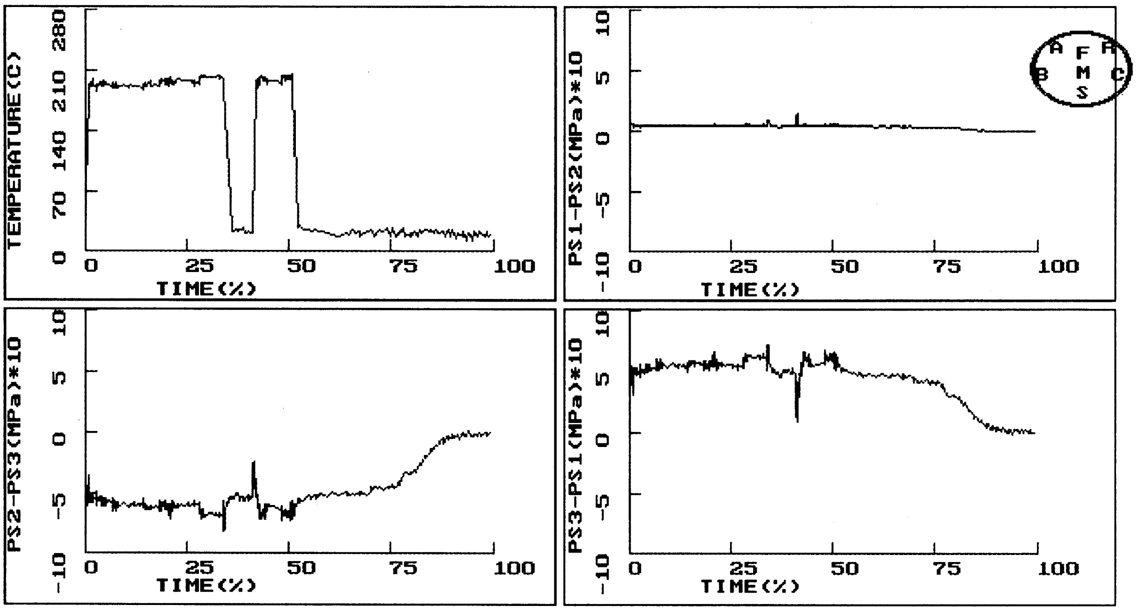

Fig. 3. The variation of computed temperature and stresses at a critical point of nozzle N02.

stresses at a selected point of N02 is shown in Fig. 3. This information is very crucial is assessing how the structure responds to the change in fluid fluctuations. It is observed that the temperature of the structure at that selected point (Fig. 3) closely follows the fluctuations of the process fluid temperature (Fig. 2). The minor fluctuations in the process fluid temperature also causes similar fluctuations in the structural temperature. In the present FMS, the computed stresses due to internal pressure, thermal load and system induced loads are stored as stress intensities which is the difference between the principal stresses. In Fig. 3 the difference of principal stress in direction 1 and 2 is denoted by (PS1-PS2). Similar definition is used for (PS2-PS3) and (PS3-PS1). The (PS1-PS2)is around 6 MPa for almost all the time with little change in its value (maximum value is 15 MPa). The variation in (PS2-PS3) and (PS3-PS1) are much more compared to (PS1-PS2). The peak value in (PS-PS3)is around -80 MPa and that of (PS3-PS1) is 75 MPa. Both of these values gradually reduce to zero during the major shut down of the plant.

The fatigue usage information of the same point is shown in Fig. 4. The stress frequency spectrum is calculated from stress histories using the rainflow cycle counting algorithm. The analysed cycles are shown here in the form of a bar chart. The fatigue usage factors are calculated from each stress cycles using material fatigue data. The final fatigue usage factor is displayed on a logarithmic scale. The usage factor at this point is low (1.2×10^{-5}). The fatigue usage factor history is also displayed (Fig. 4). How the fluctuations in process parameters affect the fatigue usage factor can be assessed from this information (Fig. 4). This figure shows the rise in usage factor due to the shut down, start up and again due to the major shut down.

Whole-field information for stresses, temperature and usage factors are also available for all the three nozzles. As has been described in Section 3, the whole-field information of stresses and temperature during the most severe condition is available on display. For fatigue usage factor the latest updated information is available. The usage factor information of N02 subjected to process parameter fluctuation is shown in Fig. 5. The

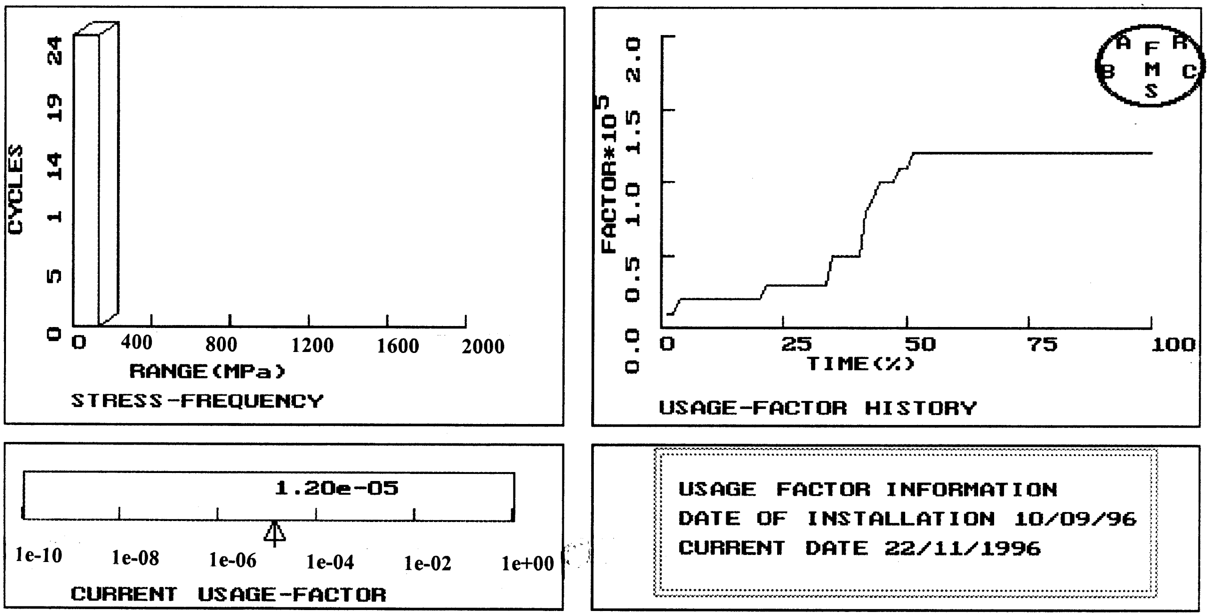

Fig. 4. The counted rainflow cycles and usage factor history of a critical point of nozzle N02.

maximum usage factor is 7.8×10^{-5}. As expected the fatigue usage factor is maximum near the nozzle vessel junction. The fatigue degradation contour information will help in taking important decisions regarding the need for non-destructive examinations, repair/replacement of the component, life assessment and life extension etc. Again the non-destructive examinations can also be concentrated on the regions where computed fatigue usage factors are high. Similar information are also available for the other nozzles.

5. Discussion

The fatigue monitoring system is running continuously in HWP Kota. The system is based on direct finite element solution for on-line fatigue monitoring instead of Green's function technique. The performance of the system is satisfactory. The whole computation is performed in a P.C. 486. The speed of processing of records has been found to be fast enough to enable it for on-line fatigue monitoring. This shows that it can be utilised for monitoring fatigue degradation for a multiple number of components using a single P.C. 486. The FMS will be installed at few other heavy water plants in India, shortly. This system can also be used to monitor the fatigue degradation of power generation industries, chemical process industries or other relevant plants.

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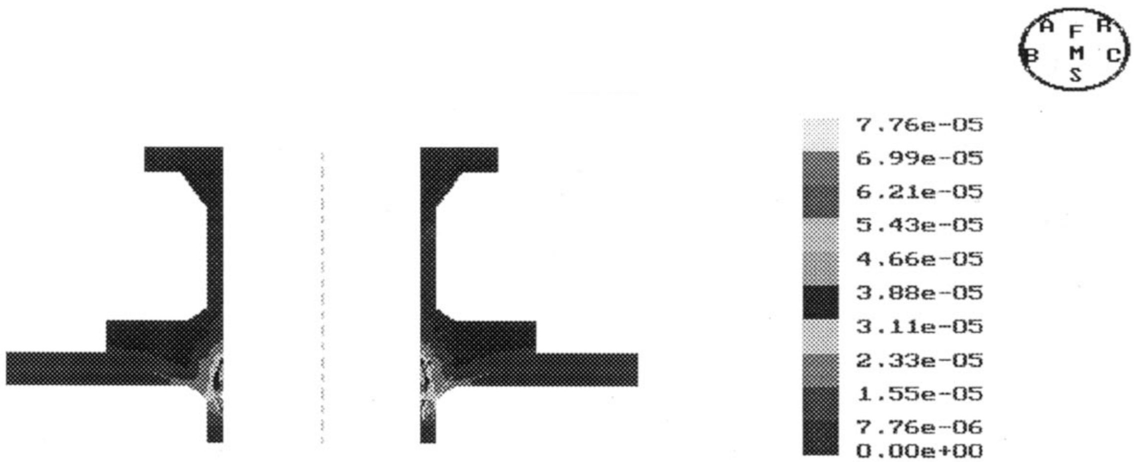

Fig. 5. The fatigue usage factor contour of nozzle N02.

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