THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

98-GT-456
~~97-GT-456~~

ON-LINE & OFF-LINE STEAM TURBINE COMPONENT STRAIN STATES MONITORING FOR THE DIAGNOSTIC SYSTEM

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ABSTRACT

This paper presents the main assumptions and targets of the strain and stress states modelling of the steam turbine components. The analysis is undertaken due to the main components of HP and IP turbine sections (inner and outer casings, valve bodies and rotors) working under a significant load. Stress modelling has been divided into two parts: a simplified analysis and the detailed one. The former has been proposed in this way that the on-line calculations can be done. It's based on special functions built upon multi-variant heat process simulations. The functions mentioned make it possible to describe the maximum component stress from some measured temperatures. This part should meet the requirements due to the stress state modelling during a usual turbine operation.

The detailed analysis comprises the unsteady operating conditions, bearing the stamp of intensive heating or cooling processes. As a result of the advanced calculation methods and full stress models being used the analyses is carried off-line.

LIST OF SYMBOLS

a - crack dimension
C^* - Landes Bagley parameter
K - stress intensity factor
N - number of cycles of operation
N_A - allowed number of cycles of operation
t - operating time
t_B - allowed operating time
T_i - temperature at point i (Fig. 3)
V - temperature rate
Z_t - creep life consumption (Eq.1)
Z_z - low cycle fatigue life consumption (Eq.11)
ε^E – elastic strain
ε^c – creep strain
σ - stress
σ_{max} - maximum stress
ω - damage parameter

INTRODUCTION

Modelling turbine components strain states is a part of a diagnostic system created for large power generating units. Those simulation modules should take charge of safe turbine operation concerning some material degradation processes.

The analyses are to assess the computational components life consumption, which eventually ought to be corrected with some non-destructive or destructive tests. The destructive tests are made for old age components.

The central part of the simulation modules is a set of algorithms and programs used to model heat and stress states of the components mentioned. In comparison to the existing treatments of this sphere in the described system particular attention has been paid to:

- component load history,
- particular turbine work conditions and following thermal and mechanical boundary conditions,
- material creep and fatigue processes.

Presented at the International Gas Turbine & Aeroengine Congress & Exhibition
Stockholm, Sweden — June 2–June 5, 1998

A very important stage of the theoretical analysis of a turbine technical state assessment is the determination of the danger of crack initiation and crack propagation rate. This analysis should concern not only the already detected defects and cracks but also the supposed ones. This issue is particular important for rotors with a central hole, where the crack frequently originates. The analyses can also be used for pressure components like turbine valves and casings.

The discussed system has been used to life assessment of steam turbine components, but the same approach may be applied to gas turbines components. In references [1] and [2] applications of similar diagnostic systems for steam piping and nuclear reactor component are presented.

THE ASSUMPTIONS AND RANGE OF MODELING

The examination carried out here complies with the following assumptions:

- The strain states of the turbine main components / casings, rotors, valves/ and their respective life consumption are evaluated continuously on the basis of a continuous measurement of appropriately chosen characteristic values. The subject of the analysis are thermally loaded components operating in high and extremely changeable temperatures /the HP and IP turbine components/.
- The general range of the measurements characterising the thermal and stress states of the main components comprises:

  - the measurement of the steam parameters within the HP and IP turbine components.
  - the measurements of the metal temperature in chosen points of the casings and valves of the HP and IP components.
  - the measurements of thermal elongation.

The actual measurement range should be adjusted to the actual turbine in question.

- Basic data:

- the real geometry of the components considered,
- the degree of life consumption,
- material specifications including strain and creep curves,
- the turbine working record,
- the turbine maintenance record.

- The task solving was divided into several more specific stages.

- a detailed description of the turbine operating conditions and the resulting thermal and mechanical boundary conditions.
- monitoring of the steady thermal-strain states / steady turbine operation under nominal or partial load/. Owing to the high temperature factor in the HP and IP component, allowances should be made for the creep process in numeric simulations.
- simulation of unsteady states /starting, power change, natural or forced cooling, extraordinary operating conditions/.
- monitoring of the crack propagation.
- determination of the fractions of fatigue and creep life consumption.

- We assume that the complete life consumption of component Z is a sum of life consumption resulting from creep while steady operation proceeds Z_t and the low-cycle consumption during changing operation Z_2. Accordingly, numeric simulations of these processes must be carried out.

Reaching the life consumption limit value Z_1 is treated as a probable moment of the appearance of the first cracks and involves more non-destructive examinations of the component in question.

PRACTICAL MONITORING REALISATION

The general chart for the monitoring of thermal-strain states is shown as follow:

I. temperature measurements
II. thermal field calculations
III. stress and strain calculations
IV. life consumption

Because of the way in which the thermal-strain states are determined, two modes of monitoring are postulated on two interrelated levels:

- ON-LINE mode,
- OFF-LINE mode.

For typical operating conditions it is possible to establish the relations which will connect the steam and metal temperature parameters with the stresses in chosen points of the component. Considering these interrelations it is possible to find the function of transition f(x), which in turn will make it possible to convert the measurement results to stresses.

$$\sigma = f(x_i)$$

where x_i are temperature derivatives or temperature differences in measured points.

On-line monitoring can thus be presented as the following relation: **measurement temperatures ⇒ transition function ⇒ stresses in chosen points ⇒ life consumption**

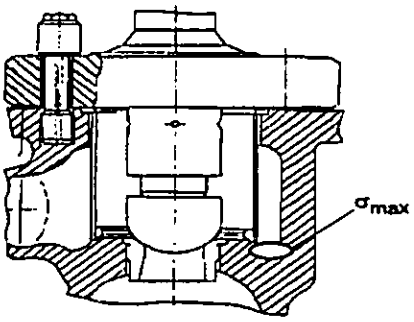

Fig. 1 The area of maximum stress (HP valve)

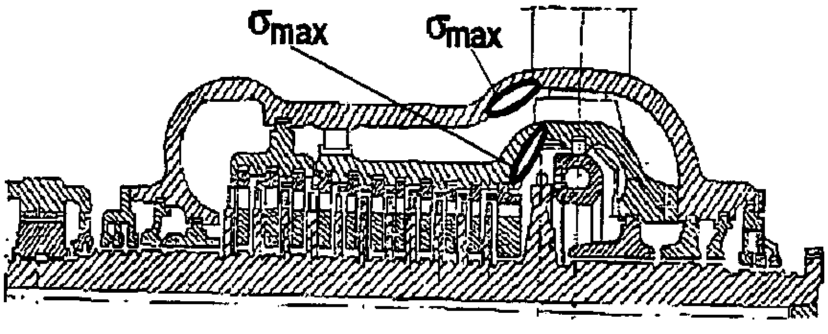

Fig. 2 The areas of maximal stress (HP casings)

In the proposed system the stresses are analysed only in the most loaded parts of the components. Those parts in the HP casing and the valves of turbine were shown in Fig 1 and 2. The location of those areas is established by means of a multivariant simulation of stresses for typical operating conditions.

With the same type of record, off-line monitoring can be presented as follows:

temperature measurements ⇒ FEM calculations ⇒ stresses in component ⇒life consumption

The above described procedure should be applied in the analysis of unsteady operating conditions, failures or substantial changes of the current working conditions or modernisation of the turbine components.

ON-LINE MONITORING

The analysis of steady conditions

Life consumption of thermally loaded components in steady operating conditions depends on the creep process. The basis for the analysis is then the distribution of stresses calculated in the main parts of the turbine accounting for the creep process.

The problem has so far been neglected or simplified. For example, components operating in the creep conditions were treated as elastic bodies. And the stresses thus calculated were the basis of evaluation of the creep life.

This system of on- line monitoring accounts for creep in steady operating conditions and the variation in the conditions (especially temperatures) is accounted for by means of the Larson-Miller parameter. To simplify the analyses, the examined components are treated as equally heated (the temperatures are balanced).

For each level of stress, temperature and the given working time t the fraction t/t_B is determined, where t_B is the allowed working time under a given stress. The sum of thus determined fractions

$$Z_t = \sum_{i=1}^{n} \frac{t_i}{t_{Bi}} \qquad (1)$$

is the life consumption caused by creep for n levels of stresses.

The analysis of unsteady conditions

The basic task of this simulation module is to model the stresses in the turbine components in on-line mode and the comparison with the assumed life consumption criterion under any operating conditions with particular emphasis laid on the starting processes from various starting thermal states and changes of power. The following condition was assumed as a basic criterion :

$$\sigma_{max} \le \sigma_{all} \qquad (2)$$

It postulates keeping the maximum stress (σ_{max}) in the turbine components below the allowed value (σ_{all}).

In this idea of the module the maximum stresses σ_{max} in the turbine components are determined on the grounds of the measurements of steam and metal temperatures in chosen points of the turbine. The points were chosen so that the checking of the thermal and stress state should comprise the following:

- the HP and IP valves,
- outer and inner HP and IP casings,
- HP and IP rotors.

In the theoretical consideration that follows, three ways of mounting the sensor in the thickness of the component wall were examined: shallow, middle and deep (Fig. 3).

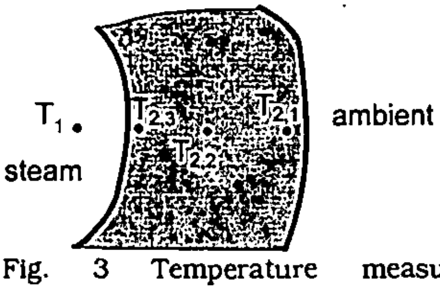

Fig. 3 Temperature measurement of component wall.

Accordingly, the following characteristics are determined:

- the steam-metal difference (ΔT)

$$\Delta T = T_1 - T_2 \qquad (3)$$

- the rate of the steam temperature change (V_o)

$$V_o = \frac{dT_1}{dt} \qquad (4)$$

- the rate of the metal temperature change (V_m)

$$V_{mi} = \frac{dT_{2,i}}{dt} \quad i = 1,2,3 \qquad (5)$$

-the difference of the metal temperatures (ΔT_m)

$$\Delta T_{m1} = T_{2,1} - T_{2,2}$$
$$\Delta T_{m2} = T_{2,2} - T_{2,3} \qquad (6)$$
$$\Delta T_{m3} = T_{2,1} - T_{2,3}$$

where T_1- the temperature of the steam in the valve

$T_{2,i}$- the temperature of the valve wall

It is assumed that the evaluation of the thermal and stress state of the turbine components (casings, valves and rotors) will be carried out simultaneously with the check of the above mentioned characteristic steam - metal, metal - metal differences, the rates of steam temperature change and the rate of heating the components. According to that, the maximum stresses in the components are determined and then compliance with equation (2) is checked.

The practical realisation of such simplified analysis of the thermal and stress state of the turbine components calls for the description of the following dependencies:

Dependence 1. Between the rate of the temperature change and the maximum stresses.

$$\sigma_{max} = f(V_o) \qquad (7)$$

Dependence 2. Between the rate of the component heating and the maximum stresses

$$\sigma_{max} = f(V_{mi}) \quad i = 1,2,3 \qquad (8)$$

Dependence 3. Between the difference of temperatures in the thickness of the component wall and the maximum stresses.

$$\sigma_{max} = f(\Delta T_{mi}) \quad i = 1,2,3 \qquad (9)$$

The above shown dependencies can be determined by means of a multivariant numeric simulation of the process of the heating and cooling of the main turbine components. For stress analysis in rotors dependence (7) is used. For valves and casings the higher values of stresses form dependencies (8) and (9) are taken.

To determine dependencies (7), (8) and (9) the actual turbine heating process was modelled. In this model the level of stress depends on the rate of change of live steam parameters.

The numeric simulation of the heating process while starting was carried out for the following rates of steam temperature change:

V_o = 1, 2,..,8 K/min

For each case the distribution of temperatures and stresses in the components examined were determined. The most important are the distributions of temperature and stresses for the maximum values.

For the illustration of the methodology which was worked out, two numeric examples are given.

Example 1.Maximum stress dependence on the valve heating rate.

The behaviour of the metal temperature derivative in three chosen temperature measurement points (temperatures $T_{2,1}$, $T_{2,2}$ and $T_{2,3}$) while the numeric simulation of the heating process was analysed.

The obtained results were the basis for working out characteristic time variations of the maximum stresses and of the heating rate for the component in question (Fig. 4.)

The analysis of the time variations shown in Fig. 4. points to a close similarity with changes in heating rates and the stresses, which corroborates the interrelation between the heating rate and the maximum stress. Thus stress states can be determined by observing the heating rate.

In the detailed model presented here only temperature $T_{2,2}$ and the heating rate

$$V_m = V_{m2} = \frac{dT_{2,2}}{dt}$$

were considered.

To determine the dependence

$$\sigma_{max} = f(V_m)$$

all the time variations were charted in a co-ordinate system σ, V_m. The results obtained in this way were shown in Fig. 5.

Example 2. Maximum stress dependence on the temperature difference in the wall thickness of the casing. While modelling the heating process (see below) additionally the changes in temperature differences in the component wall thickness were analysed (ΔT_m).

The aim of this task was the determination of the dependence between the temperature difference in the wall thickness and the maximum reduced stresses.

$$\sigma = f(\Delta T_{mi}) \quad i = 1,2,3$$

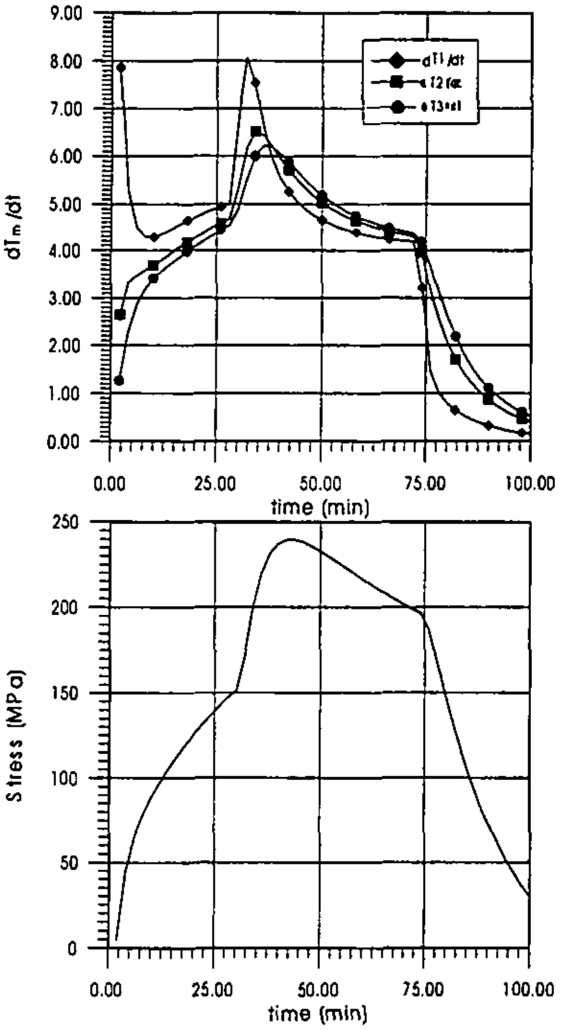

Fig. 4. Time variations of the maximum stresses and heating rates at 3 points of the component for
$V_0 = 2K/min$.

The results served as a basis for working out the characteristic time variations of the maximum stresses and temperature differences in the wall thickness of the examined component (Fig.6.). In the detailed analysis only the differences $\Delta T_m = \Delta T_{m1} = T_{2,1} - T_{2,2}$ were considered.

To determine the dependence

$$\sigma_{max} = f(\Delta T_m)$$

all the time variations shown in Fig. 6. were charted in a co-ordinate system σ, ΔT_m. The obtained results are shown in Fig. 7.

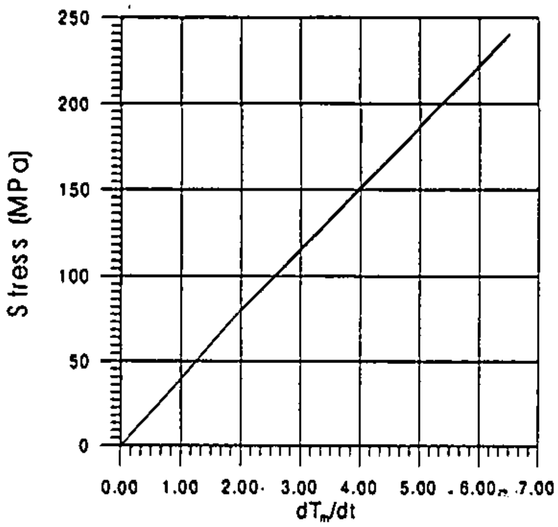

Fig. 5. Maximum stress dependence on the heating rate

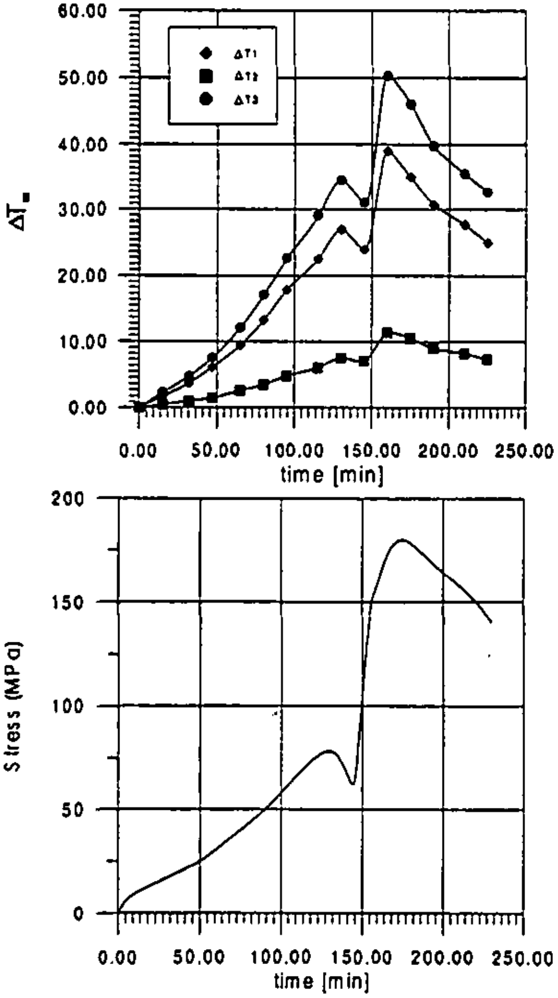

Fig. 6. Time variations for the maximum stresses and temperature differences in the component wall thickness for V = 2K/min.

The starting point to determine fatigue life consumption are the amplitudes of total strain $\Delta\varepsilon_t$. From the fatigue characteristics

$$\Delta\varepsilon_t = f(N_A) \qquad (10)$$

the number of cycles leading to the first cracks and the fraction of the fatigue $Z_z = N/N_A$, (where N is the real number of cycles) are determined. The total strains $\Delta\varepsilon_t$ are evaluated as a function of stress according to the TRD standard [8]. Low-cycle fatigue life consumption during unsteady operation can be written in the following form:

$$Z_z = \sum_{j=1}^{m} \frac{N_j}{N_{Aj}} \qquad (11)$$

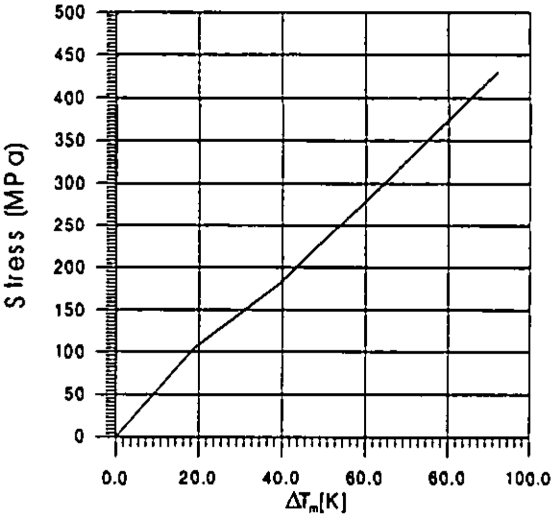

Fig. 7. Dependence of maximum reduced stresses on temperature difference ΔT_m.

The above dependencies were based on the linear Palmgren-Miner's hypothesis of failure summing. It assumes that the ultimate life consumption occurs when fatigue Z reaches its critical value.

After the component reaches the critical fatigue level, systematic non-destructive examination should be started together with intensified monitoring of the turbine component in use because of a higher chance of failure.

On-line monitoring of the crack propagation

Crack propagation occurs under cyclical loads caused by starting and power changes, as well as under unsteady operating conditions. The increment of crack propagation in one operating cycle will be the sum of the growth caused by the cyclicity of operation Δa_N and the steady operation time in this cycle Δa_t. A general equation describing this propagation is the following [3]:

$$\frac{da}{dN} = \frac{da}{dN_N} + \int_0^{t_n} \frac{da}{dt} dt \qquad (12)$$

where t_n is steady operation time in a given cycle.

The first part of the equation describes propagation caused by the cyclicity of operation; the second describes the propagation under steady operating conditions. Using the stress intensity factor K and Landes Bagley C* parameter [4] the above equation becomes:

$$\frac{da}{dN} = A\Delta K^n + \int_0^{t_n} DC^{*m} dt \qquad (13)$$

where A, D, n, m are constants.

Solving the equations in on-line mode is not difficult but it involves the calculation of the scope of the stress intensity factor change ΔK and parameter C*, which in turn calls for the calculation of the component stresses in the crack area. In on-line mode the values must be approximated.

OFF-LINE MONITORING

The construction complexity of turbine components and the potential variety of operating conditions is the reason for which the assessment of the life consumption sometimes must be carried out by means of more detailed methods. It is a requirement during extraordinary operating conditions e.g. during failures causing abrupt thermal changes in components. Such failures involve water or leaks of much cooler steam into the flow system.

The change in the operating conditions, which may change the thermal and mechanical loads of components, and, consequently, life consumption, especially the creep life usually requires the complement of the calculations of life consumption in the on-line mode. Also any modernisation of turbine components requires an exact assessment of life consumption carried out in off-line mode.

Off-line monitoring is based on an archived record of parameters obtained in continuous measurement used in on-line monitoring. In the off-line calculations, more exact analysis methods like the finite element method are used, which makes it possible to account for the thermal and mechanical boundary conditions and, depending on the model employed, allows better evaluation of geometry of the components.. Such an analysis enables tracking thermal states and the level of stresses in whole components.

Off-line analysis can evaluate all the crucial processes contributing to the decrease of durability i.e. low cycle fatigue, creep and crack propagation. With off-line monitoring both destructive and non-destructive examinations can be carried out. The results obtained allow the correction of the assessment of the life consumption and updating of the assessment of the current technical state of components.

Low-cycle fatigue

A recorded amplitude of stress occurring in a given operating cycle is used for the current assessment of life consumption caused by low cycle fatigue. In more detailed analyses modeling stress states by the finite element method the temporary stress changes are also recorded giving local amplitudes in all calculating points of the component. Working out such variations by the e.g. „rain flow" method [2] allows an even more exact evaluation of the growth of life consumption in the analysed period.

An off-line analysis allows the use of elasto-plastic algorithms. It applies especially to the places of concentration of stresses and thermal shock analyses, which may cause considerable plastic strains. An application of the finite element method is more efficient but is much more time consuming, which excludes carrying out such analyses in on-line mode.

Creep

The analysis of creep by means of the finite element method is based on the following assumption:

- the total strain is decomposed into two components: elastic and creep one

$$\varepsilon = \varepsilon^E + \varepsilon^c \qquad (14)$$

- the relation between the strain and stress change is of the form:

$$\Delta\sigma = D\left(\Delta\varepsilon - \Delta\varepsilon^{c}\right) \qquad (15)$$

where D is the matrix of elasticity

- the constitutive equations take the form [5]

$$\frac{d\varepsilon_{ij}^{c}}{dt} = \frac{3}{2}B\frac{\sigma_{i}^{n-1}}{(1-\omega)^{n}}\left(\sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}\right) \qquad (16)$$

where ε^{c}_{ij} - creep strain tensor

σ_{ij} - stress tensor

σ_{i} - effective stress

ω - damage parameter

B,n - material constants

- damage is represented by a scalar parameter ω [5]

$$\frac{d\omega}{dt} = M\left(\frac{\sigma_{eq}}{1-\omega}\right)^{\nu} \qquad (17)$$

where $\sigma_{eq}=\alpha\sigma_{1}+(1-\alpha)\sigma_{i}$

σ_{1} - maximum principal stress

α,ν,M - material constants

- for time integration Euler's procedure was used.

Details of the algorithm are given in [6]

Crack propagation

Off-line monitoring of crack growth is based on two essential tasks. The first is a calculational one. It consists in finding by means of the finite element method the value of the component stresses leading to the real or assumed crack. The resulting values allow a more exact calculation of the stress intensity factor K and the index of cycle asymmetry, which in turn makes it possible to use more complex dependencies describing the propagation of crack.

The other task feasible under off-line mode is the examination of crack location and its size. Such examinations are carried out by means of endoscopes equipped with devices reading and recording the discontinuity of the material in the areas involved. The results obtained allow a more exact analysis of the crack propagation rate and a correction of the calculations of the crack size.

Probabilistic analysis

A number of the values used for the assessment of durability are random values. This is the case with the temperatures of metal (measured values), maximum stresses in an operation cycle (values calculated) or standards characterising material strength (catalogue values). All this results in the calculated life time being a random value as well.

Using probabilistic analysis algorithms and working out required probable characteristics for input data it is possible to assess the probability of the component failure as a function of time.

$$P_{f} = P\left(t_{f} - t \leq 0\right) \qquad (18)$$

where: P_{f} - probability of failure, t - operating time, t_{f} - predicted life time

The random value t_{f} contains all uncertainties of measured temperature, calculated stresses, material constants, etc.

Because such analyses are extremely complex and time consuming, they can only be carried out in off-line mode [9]. More experience is necessary and better probability characteristics have to be worked out before on-line mode analysis can be applied.

A LIFE TIME MONITORING SCHEME.

The above consideration of on-line and off-line monitoring allow a definition of a general life monitoring scheme (Fig. 11), in which both modes complement each other and contribute to a reliable assessment of the technical state of the turbine components. On the grounds of measurements of the steam and metal parameters the stress state is determined in a simplified and an exact way in on-line and off-line modes, respectively. In the next stage during on-line mode there is a current calculation of low cycle fatigue N/N_{a} and creep t/t_{B} life consumption and the total consumption is found. Thus obtained consumption is then verified by analyses (calculations and non-destructive examinations) in off-line mode. Similarly, the crack growth caused by cyclic loads and steady operating conditions may be calculated.

An example of 200 MW turbine monitoring is shown in Fig. 9 and 10. Nominal steam inlet parameters for turbine in question are: temperature 540°C, pressure 13.5 MPa. The turbine has been worked over 150000h. The following quantities have been measured : live steam temperature, metal temperatures of HP and IP valves, inner and outer casings. An exemplary time variation of live steam temperature of HP casing is shown in Fig. 8.

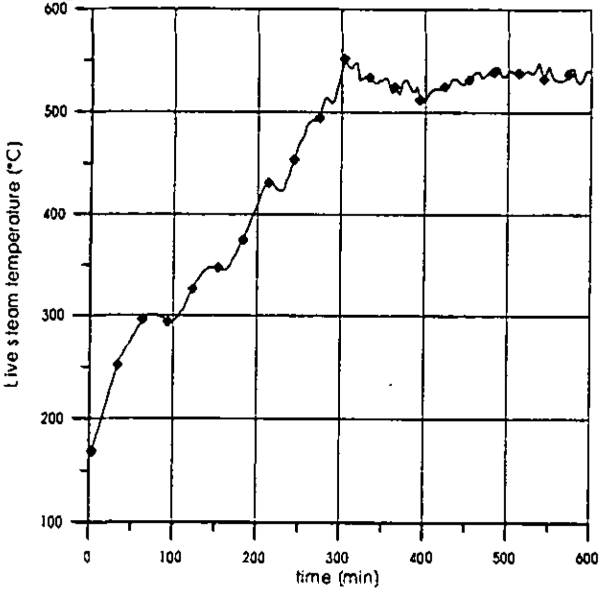

Fig. 8 Time variation of live steam temperature.

The exemplary values of the growth of life consumption of the main turbine components: HP valves, HP casing, HP rotors, IP valves, IP casing, IP rotors verified during the latest maintenance work by off line monitoring (exact calculations, non destructive examinations: replicas, magnetic particle testing, ultrasonic testing and endoscopic inspection of rotors bore) are shown in Fig. 9. Present life consumption values since the latest maintenance work are shown in Fig. 10.

CONCLUSIONS

The simulation modules for continuous modelling of the stress states of turbine components presented here can be installed as an independent system for tracking the degree of the life consumption of the main components of the machines. It can cooperate with other, more complex, generating unit diagnostic systems.

The major utility benefit associated with life monitoring in power plants is the gathering of data necessary to support analyses for the condition assessment of turbine components. An on-line monitoring system will also provide direct benefits in the areas of plant operations and maintenance.

The results of the off line probabilistic analyses provide a much more detailed and realistic basis for decision on planed life extension and inspection scheduling.

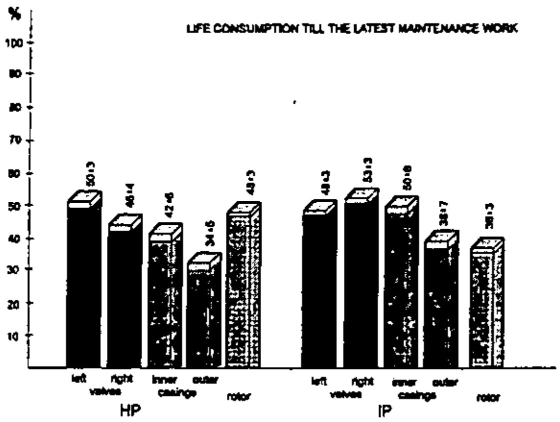

Fig. 9. Components life consumption till the latest maintenance work

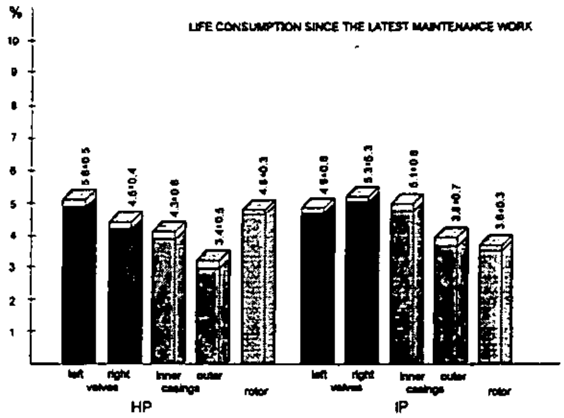

Fig. 10. Components life consumption since the latest maintenance work

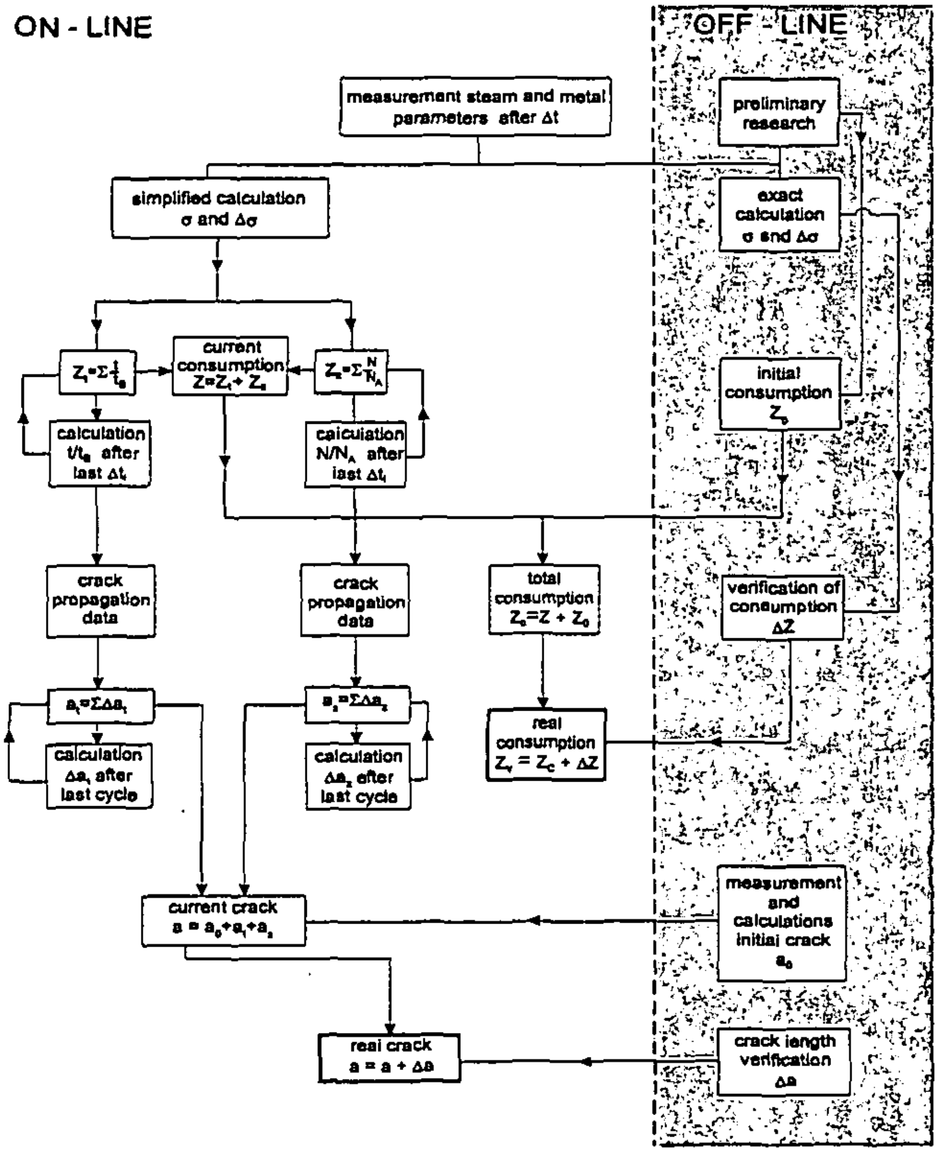

Fig. 11 Monitoring scheme.

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