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OPERATIONAL MONITORING OF THE LONG-TIME CHARACTERISTICS OF COMPONENTS - COMPUTING ALGORITHMS FOR DETERMINING THE CURRENT DEGREE OF FATIGUE

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Abstract

Operating experience in German nuclear power stations has shown that in various operating states, individual components are stressed in ways that were not known when the plant was designed (e.g. thermal stratification). Because this stresses cannot be specified without further examination, it was necessary to detect them by measuring. The first step was to install data acquisition systems.

This article introduces the computational methods employed in automatic calculation of fatigue using measured values. These methods differ distinctly from conventional stress and fatigue calculation methods. A comparison of automatic and conventional fatigue evaluation shows advantages and disadvantages.

1 Introduction

In order to eliminate fatigue failures in primary circuit components, the frequency of fatigue related loads was specified in the design. Categorised as thermal loads were global processes such as start-up and shutdown of a plant.

Operating experience has shown that, apart from this specified global loading, local fatigue related loading can occur, even during constant plant operation. What we are looking at are thermal stratification and thermal shock caused by medium with different temperature. Figure 1 shows the temperature courses measured in a surge line. Measuring plane 1 is in the vicinity of the pressurizer; measuring plane 4 is close to the primary coolant pipe. The recording was made during the loading condition "zero power cold" in which constant temperatures in pressurizer and primary coolant pipe are maintained ($T_{PR} \approx 250°C$, $T_{PCP} \approx 50°C$). The measurements show however that the temperature in the lower half of the measuring plane at the pressurizer drops close to the primary coolant pipe temperature. This temperature course occurred as a result of an insurge event in the pressurizer.

Temperature courses of such a kind can occur repeated during a specified loading case. Further non-specified loading occurs as a result of fault functions (e.g. internal leakage of an armature). As it is shown in Ref. 1, cracks and incipient cracks in primary circuit pipelines have already occurred as a result of such loading.

Since stratification and shock is caused by complicated mechanism of flow, they cannot be incorporated in the design specification.

In order to detect the influence this loads have upon component fatigue the loads must be recorded during operation. The first step was therefore to install measuring systems in nuclear power stations.

A detailed analysis of loading requires a large number of measured value sensors and a high interrogation frequency. These in turn generate large quantities of data. Special computer programs are therefore needed to calculate the fatigue using the measured values.

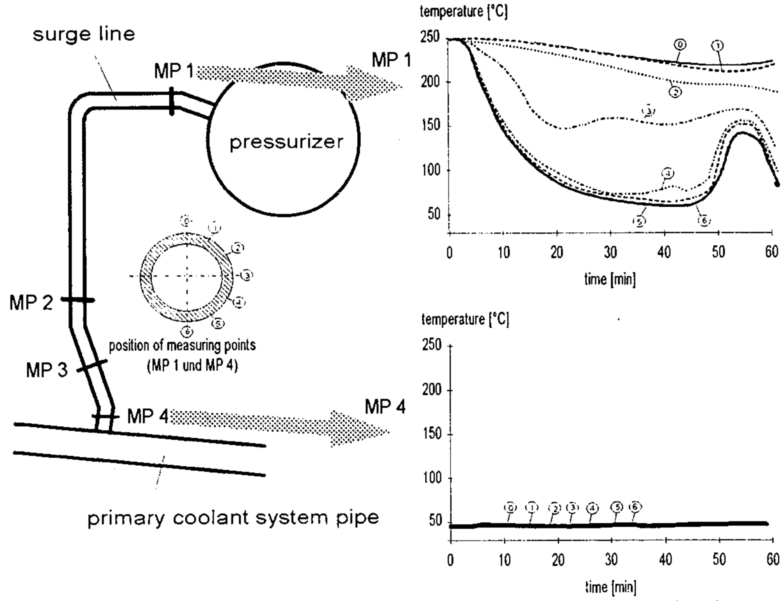

Figure 1 Surge-line including FAMOS-measuring planes (MP) and measured temperatures

This article is intended to give an introduction to the FAMOS system (Fatigue Monitoring System). Particular attention will be given to the automatic calculation of fatigue usage factors using recorded measured values.

2 The FAMOS concept

While developing FAMOS, division into 3 stages (see figure 2) proved itself to be advantageous:

- stage 1 data acquisition
- stage 2 data evaluation
- stage 3 fatigue evaluation

In stage 1 loads (e.g. temperature, pressure) are recorded and stored on a data carrier (magnetic tape or opto-disc). To acquire local loads, beside measured values from the plant-instrumentation values from a special FAMOS-instrumentation are recorded. Figure 1 shows the FAMOS-instrumentation of a surge line (MP 1 - MP 4).

Stage 2 provides

- graphic representation of measured values
- comparing measured and specified transients
- quick evaluation

The option quick evaluation is used to analyse measured value courses with regard to size and frequency of loads. Thus this stage provides a quick survey of loads on a component.

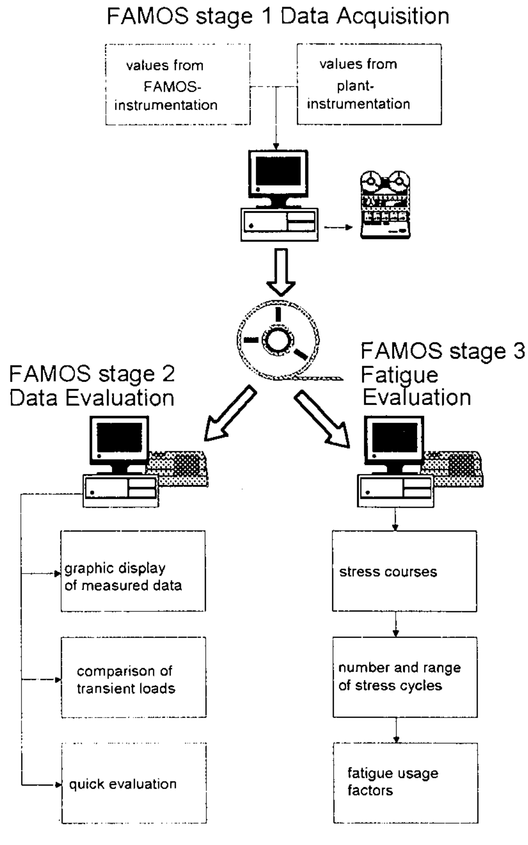

Figure 2 FAMOS functional units

The stage 3 "fatigue evaluation" will be completed by mid 1993. The first fatigue evaluations have already been carried out using a test version of the program. TÜV Bayern Sachsen's assessment of the fundamental computing algorithms has been completed. A comprehensive description of the FAMOS stages 1 and 2 is given in Ref. 2 and 3. For this reason we shall focus in particular upon FAMOS stage 3 in this article.

3 FAMOS stage 3 - fatigue evaluation

The fatigue evaluation program is used to establish the correlation between recorded loading and the proportion of fatigue resulting from this loading. The processes used in classical fatigue calculation, consisting of

- load specification
- calculation of temperature fields, using finite-element method (FEM)
- stress calculation using FEM
- evaluation of the fatigue usage factor

are largely unsuitable for application in automatic fatigue calculation. Procedures and processes used in FAMOS stage 3 are shown in figure 3.

Calculation of principal stresses $\sigma_u(t)$, $\sigma_v(t)$, $\sigma_w(t)$ is carried out separately for each individual load type. Investigated load types are:

- thermal shock
- thermal stratification
- internal pressure
- external pipe loads

The total principal stresses are the result of the superposing of the simultaneously occurring individual principal stress components.

The fatigue usage factor caused by total principal stress course is determined according to the ASME-Code (Ref. 3). For the calculation of the k_e value linearized stresses are required. Because no linear stress distribution exists across the wall during temperature shock loading, these are determined additionally.

Component related information, that is required during fatigue evaluation (geometry,

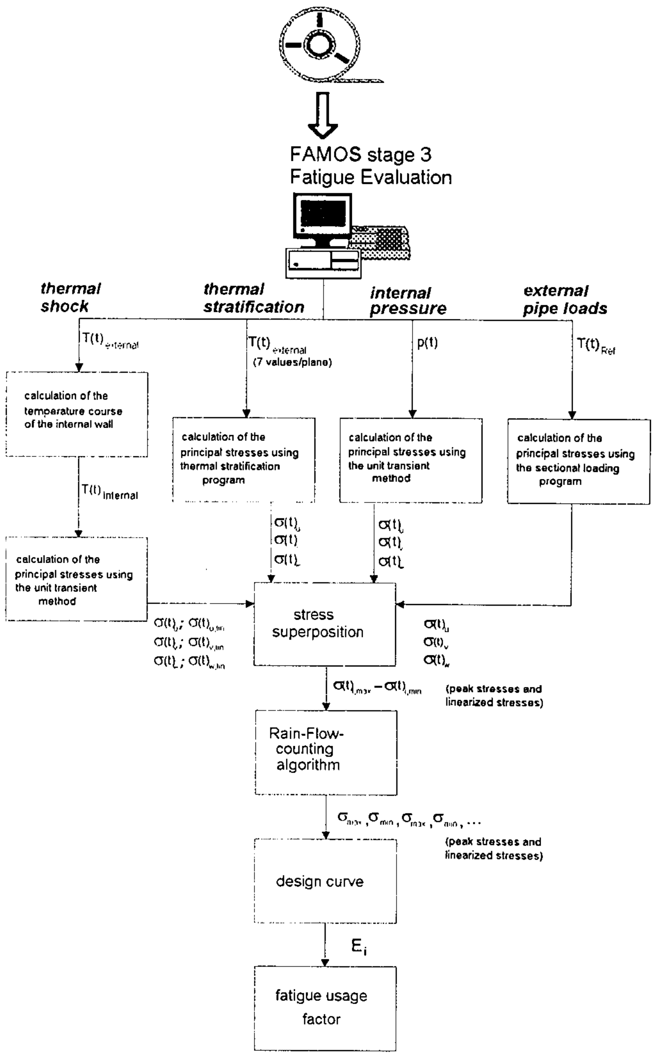

Figure 3 FAMOS stage 3 fatigue evaluation

characteristic values of materials, mounting/restraint conditions...), is stored in a component data-file.

In the following the fundamental computing algorithms are described:

Calculation of the internal wall temperature

In the data acquisition temperatures at the external surface of a component are recorded. Changes in temperature of the contained fluid give rise to changes of temperature of the component. Necessarily the maximum temperature shock loading occurs at the internal surface. In order to be able to determine the highest stresses caused by thermal shock, the temperature course at the internal surface must be calculated.

The calculation of interior temperature course using FEM is only possible iteratively and is costly.

FAMOS uses a solution of the unidimensional, nonsteady heat conduction equation to determine the internal temperature course. This solution uses a polynomial approach for the temperature course across the wall (homogeneous solution) and a time discretisation (inhomogeneous solution). To adapt to transients and component geometry, polynomial order and number of read-in temperatures on the external surface can be selected. These values are stored in the component data-file.

To qualify this process, temperature courses were applied to the internal surface and FEM was used to determine the courses at the external surface. The process was then used to calculate internal temperature courses using the before evaluated external courses.

In the case of thick-walled components a good correlation was given between the temperature courses taken as a basis and the calculated temperature courses at the internal surface (generally deviations caused an error of < 5% in the stress courses). In the case of thin-walled pipelines (s ≤ 20mm) where sharp transients are present the interrogation frequency currently employed in FAMOS (0.1 Hz) does not allow for sufficiently accurate recording of the external temperature course. Unacceptable errors (≥ 20%) thus arise in the calculation of the temperature course at the internal surface. In such cases fluid temperatures (from plant-instrumentation), which are also recorded by FAMOS, are to be used as a substitute.

Unit transient method

The unit transient method is used to calculate stresses resulting from temperature shock loading.

The stress response to a unit temperature transient is calculated for the area of the component to be examined (see figure 4.1/4.2) using FEM (this calculation is carried out before the FAMOS stress calculation). The stress response is stored in the component data-file. Linearized stresses are equally important for fatigue analysis; the stress response of linearized stresses must therefore also be calculated and stored. In the FAMOS fatigue calculation the temperature course at the internal surface is scanned with scaled unit transients (figure 4.3). The stress course is given by superposing the products of the stress responses and the scaling factors (figure 4.4).

Comparison calculations with FEM showed good correlation (max. deviation <3%).

Analogue determination of the stresses resulting from internal pressure is carried out using unit pressure transients.

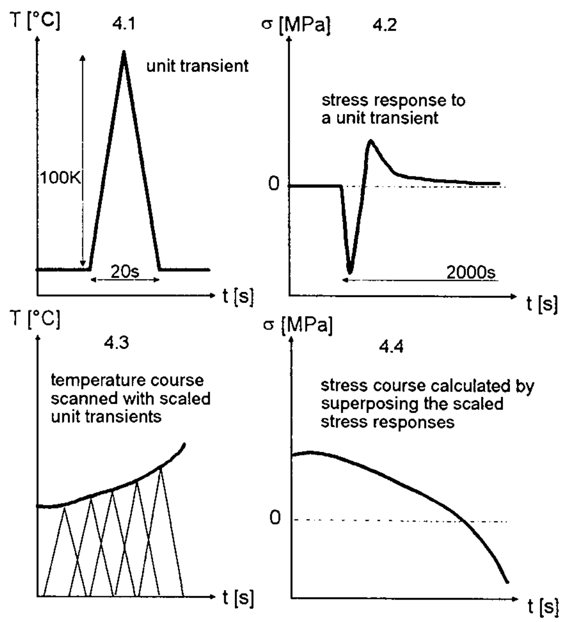

Figure 4 Calculation of thermal shock stresses using the unit transient method

Process for the determination of stresses caused by temperature stratification

The calculation of stresses resulting from temperature stratification is executed using an analytical process in which the pipe wall is represented as a shell-type model.

In the case of thick-walled pipes were sharp layers are present a temperature gradient in a radial direction also arises. The shell-type model does not take account of this effect.

Our tests showed that a maximum error of 10% could occur as a consequence of this radial gradient. In order to avoid this error suitable corrective factors are required.

Temperature stratification stresses are sensitively dependant upon the conditions under which the pipeline is mounted. These conditions can be entered into the component data-file. Preliminary examination may be necessary to determine the mounting conditions.

Rainflow counting algorithm

This process is used to reduce stress courses to a sequence of stress-differences (figure 5). When a new extreme value is reached a stress cycle (hysteresis cycle) is closed. The time of the loading is not recorded; the sequence is maintained for the fatigue evaluation.

The Rainflow counting algorithm is also used in the quick evaluation program of the FAMOS stage 2 (Ref. 2).

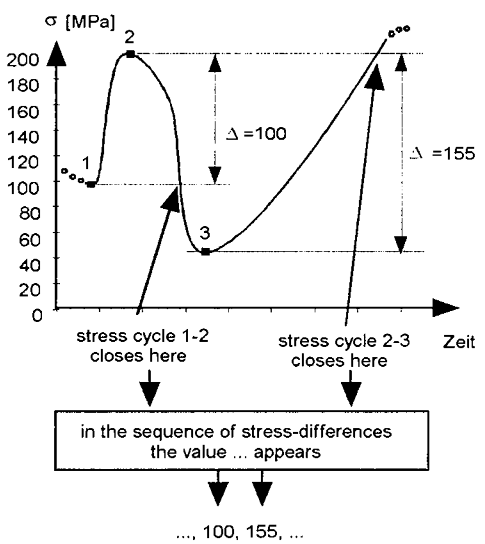

Figure 5 Reduction of stress courses to a sequence of stress-differences

4 Comparison of fatigue analyses FAMOS stage 3 ⇔ conventional procedures

The following is an attempt to clarify the FAMOS stage 3 procedure by means of a comparison with conventional fatigue analysis. Fundamental calculation units have been arranged in a table for comparison. The accuracy is given to help in judgement; these values are to be taken as rough reference values which have been derived from our tests and preliminary fatigue calculations using FAMOS.

The high error value for load evaluation in the conventional procedure was derived from a FAMOS-fatigue calculation for a surge line for two different start-up procedures which are not considered individual in the specification. Calculated fatigue fractions for these two start-up procedures deviated from each other by a factor of 25 (Ref. 5).

Because of the great uncertainty of the load determination in conventional fatigue analysis higher accuracies are achieved in the FAMOS fatigue calculations.

References

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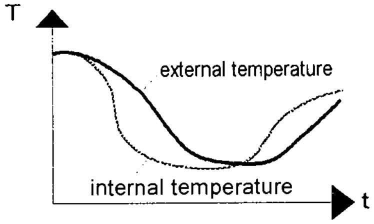
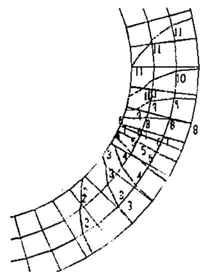
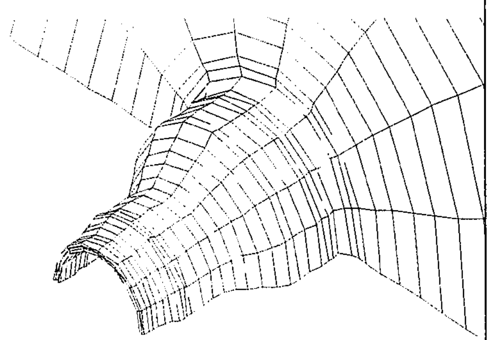
No	Calcul-ation stage	FAMOS	Conventional procedure
1	Load evaluation	Recording using FAMOS stage 1 *Error ≈ 5% (measuring accuracy)*	Compilation of loading reports • Evaluation of operational recordings • Evaluation of special measurements or FAMOS recordings in order to register temperature stratefication • Definition of model transients for the stess calculation • Determination of frequency and duration of model transients *Error ≈ factor 25 possible (see page 4)*
2	Temper-ature field calcul-ation	Determination of temperatures at the internal surface for the calculation of temperature shock stresses  Preliminary examinations are required for adaptation to geometry and transients *Error ≈ 5%*	Determination of temperature fields. Iterative solutions of internal surface temperature.  *Error ≈ 5%*
3	Stress calcul-ation	Calculation of main stresses for the individual load types and simultaneous stress super-position • Temperature shock ⇒ unit transient process (stress responses to unit temperature transients are to be determined in preliminary examinations) • Temperature stratefication ⇒ tem-perature stratefication program (mounting conditions are to be determined in preliminary examinations) • Internal pressure ⇒ unit transient process (stress responses to unit pressure transients are to be determined in preliminary examinations) • External pipeline forces ⇒ sectional loading program *Error ≈ 10%* *(As yet no test values available from deter-mination of stresses in areas of geometrical irregularity)*	Calculation of stresses for all specified tran-sients with a complex FE model. Estimation or an iterative procedure are necessary for the determination of differences in stress.  *Error ≈ 5%*
4	Fatigue calcul-ation	• Determination of stress sequence with rainflow algorithm • Determination of individual fatigue fractions using fatigue curves (E-module of temperature dependant) • Determination of total fatigue fraction *Error ≈ 5%*	• Determination of individual fatigue fractions for the specified transients • Determination of total fatigue fraction *Error ≈ 10%*