Vibration Monitoring of Pressurized Water Reactors with Indirect Measurements

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Abstract:

Damages of mechanical components manifest themselves in an early stage by changes of their vibrational behaviour. Measurements at the outside of a pressure vessel also yield information about the internal movements. The KWU Vibration-Monitoring-System employs absolute- and relative displacement-, pressure- and neutron flux transducers for such purposes. An overview about operational experiences with such systems is given. The vibration monitoring involves seven working steps.

1. Introduction

Developing or actual damages of mechanical components can be detected due to the simultaneously occuring change of the components dynamic behaviour. Therefore most of the reactors built by KWU and other reactors are equipped with a vibration monitoring system (table 1). Mainly the safety relevant components of the primary circuit are monitored (Fig. 1):

- reactor pressure vessel (RPV) with its most important internals
- main coolant pumps (MCP)
- steam generators (SG) and
- main coolant pipings (PIP)

Vibrations of these components are caused by

- the flow of the coolant
- excentric masses of the MCP
- resonances of the fluid
- transient forces during load changes of the reactor
- movements of the building at the supporting points of the components.

2. Operational experience

For nearly 20 years the dynamic behaviour of all primary circuits of the PWR's built by KWU has been determined during the comissioning period. From these measurements the important frequency range (0,5 - 100 Hz) as well as the component displacement amplitudes (0,5 - 500 μm) are known.

Further results can be summarized as follows:

- The dynamic behaviour of all KWU-PWR's is very similar, but each reactor has its own typical vibration pattern. This is inferred from the PSD-spectra of absolute displacement transducers, attached to the outside of the RPV-lid (Fig. 2).
- For dominant peaks in the PSD spectra, measured with transducers inside the reactor, often corresponding peaks occur in the spectra of signals of transducers, attached at the outside of the RPV: in Fig. 3 spectra of core barrel-(CB) and flow-skirt-(FS) motions are compared with the RPV-lid motions.
- The measured resonance frequencies of the components and the fluid change with temperature, pressure and power of the reactor. The temperature is the most important parameter. As an example Fig. 4 shows the temperature dependency of the CB- and FS-motion.
- Neutron flux signals yield information about fuel element bending modes and CB pendulum and shell modes (Fig. 5).
- There is no significant alteration in the dynamic behaviour of KWU-PWR's over many years (Fig. 6).

3. The KWU Vibration Monitoring System "SÜS"

Based on the described experience a PWR-Vibration Monitoring System (in German: "Schwingungs-Überwachungs-System": SÜS) has been designed, developed and tested, partly with financial aid by the German government. This SÜS is optimized to be sensitive to very small alterations of the dynamic behaviour of the primary circuit and the reactor internals. Thus damages can be seen in the initial stage and consequent damage on a larger scale can be avoided. Optimization means, in this case, the development of a system, that gives a maximum of information for the monitoring task without an added risk to the reactor operation. This is a difficult to achieve objective with respect to the reactor internals, because direct measurements at these components are not possible. The primary circuit is not accessible during reactor operation. This is an additional difficulty for the system. However the coupling between RPV and CB of KWU PWR's allows the measurement of the CB-motions indirectly at the outside of RPV with very sensitive displacement transducers.

The optimization led to transducer locations as shown in Fig. 1 for the example of a KWU 4-loop-PWR. The following types and numbers of transducers are installed:

- 4 absolut displacement transducers (type A), to measure the RPV motions
- 5 pressure transducers (type P), to measure the pressure fluctuations of the fluid

- up to 16 relative displacement transducers (type R), to measure the displacement of different points of the primary circuit relative to the building
- 8 neutron flux transducers (type X) to deduce the fuel assembly and CB motions.

The transducers were developed by KWU (A) or bought from external suppliers (x) and modified for the vibration monitoring task (R, P). All transducers can easily be exchanged. The types A and R can be calibrated remotely from central cabinets, where the signal conditioning and data evaluation equipment is installed.

4. Test results with a SÜS

For evaluation of the measurement first PSD-spectra of all SÜS-signals are calculated. These vary for different types of signals. The information in the spectra is partly identical, partly complementary. The peaks can be assigned to resonances of the structures and the fluid or to forced vibrations. In the following, a short spectrum description for each type of signal is given:

- A PSD-spectrum of a RPV-lid-signal (type A) is shown in Fig. 7. The peaks correspond to (1) RPV/CB-pendulum- and (2) RPV-vertical-motions, (3) fuel-assembly first bending mode, (4) flow-skirt first bending mode, (5) fluid resonances and (6) influence of MCP revolution.
- A pressure fluctuation PSD-spectrum (type P) is shown with Fig. 8. Most of the peaks are due to fluid resonances (5).
- In the spectra of relative displacement transducers (type R, Fig. 9) peaks due to pendulum modes of MCP (7), SG (8) and piping modes (9) are present.
- The neutron flux spectra (type X, Fig. 10) contain information on CB pendulum modes (1), fuel assembly bending modes (3) and CB shell modes (10).

The correspondence of the observed peaks to the resonances of the monitored structure can only be established with the aid of additional activities or information such as:

- computational modal analysis,
- experimental modal analysis /2/,
- evaluation of commissioning measurements with correlation techniques.

Two examples for the last category are presented:

Coherence spectra of A-type signals are shown in Figs. 11 and 12. Strong coherence for RDB/CB pendulum motions between signals from transducers at opposite location of the RPV lid is observed. The coherence of signals from neighbouring transducers is low. Figs. 13 and 14 clearly indicate, that the first RPV/CB pendulum mode of Fig. 12 at 7,5 Hz is infact a mode, where the RPV moves relative to the CB, while the second pendulum mode at 12,6 Hz does not imply a relative displacement between RPV and CB.

The result of all above mentioned activities is a good understanding of the dynamic behaviour of the primary circuit. It is characterized by the Eigenfrequencies and Eigenforms. The most important ones of them for a KWU-PWR 4-loop plant are shown in Fig. 15. The knowledge of these Eigenvalues for specific plants is a necessary basis for efficient vibration monitoring.

5. Vibration monitoring working steps

Vibration monitoring usually consists of comparisons of actual signals or signal patterns with reference signals or signal patterns. Usually in Germany three measurements are performed per fuel cycle.

The KWU vibration monitoring procedure will include seven working steps (Fig. 16). These different steps are as follows:

MEASUREMENT:	Measuring of signals in the time domain.
TRANSFORMATION:	Fourieranalysis and fouriertransformation of the signals.
MARKING:	Selection of prominent peaks in the fourierspectra.
IDENTIFICATION:	Association of marked frequencies f_m with the appropriate Eigenforms.
NORMALIZATION:	Transformation of actually measured frequencies f_m to frequencies f_N at operational conditions, at which reference frequencies f_v have been measured.
COMPARISON:	Normalized frequencies are compared to reference frequencies, the differences are evaluated.
VALUATION:	Association of frequency deviations /1/ and its cause. Check, whether deviations exceed preset limitations. Formulation of further action.

These seven tasks of the vibration monitoring can also be assigned to a computer system, if the Eigenfrequencies and Eigenforms, their dependence on the operational parameters /1/ and criteria for the limits of the frequency deviations for each important peak have been incorporated in the associated computer codes.

/1/ H.-J. Wehling, K. Klingler, H. Stölben: The infl. of thermohydr. par. on the dyn. beh. of KWU-PWR plants. SMORN 6, Dijon, France, Oct. 1984

/2/ H.J. Wehling, W. Schüz, D. Wiemerslage: Experimental Modal Analysis - an auxiliary means in Reactor Vibration Monitoring. 18th Inf. meet. on React. Noise, Praque, Czechoslovakia, April 1985.

SÜS / Plant	Country	Transducertype, number				Year of delivery
		A	R	P	X	
GKN	D	4	6	4	8	1976
KKU	D	4	8	4	8	1978
KWB-A	D	4	–	–	–	1982
KWB-B	D	4	–	–	–	1982
KKG/BAG	D	4	16	4	8	1983
Dukovany 1	CS	4	4	–	–	1983
Bohunice 2	CS	4	4	–	–	1984
KKP II	D	4	16	5	8	1984
Grohnde	D	4	16	5	8	1984
Dukovany 2	CS	4	12	–	–	1984
Brokdorf	D	4	16	5	8	1985
Dukovany 3	CS	4	12	3	–	1985
Bohunice 1	CS	4	4	–	–	1985

Table 1: Vibration Monitoring Systems built by KWU

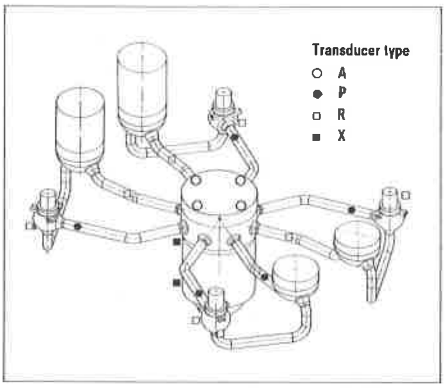

Fig. 1: Primary circuit and location of SÜS transducers

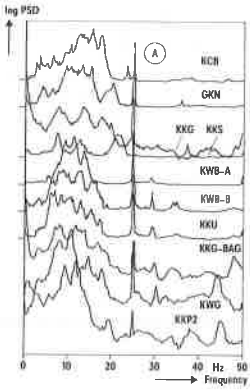

Fig. 2: PSD-spectra of A-type signals of PWR plants built by KWU

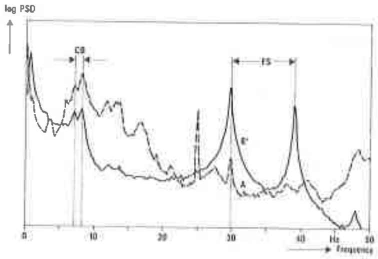

Fig. 3: Comparison of RPV and RPV-internals vibrations

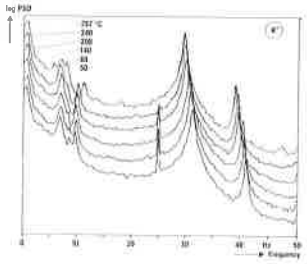

Fig. 4: Influence of temperature on the CB and FS resonances

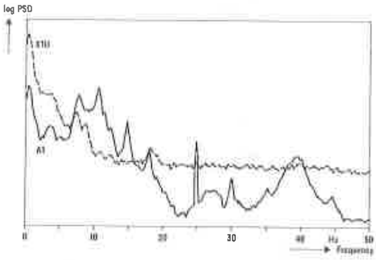

Fig. 5: Comparison of the spectra of RPV displacement and neutron flux

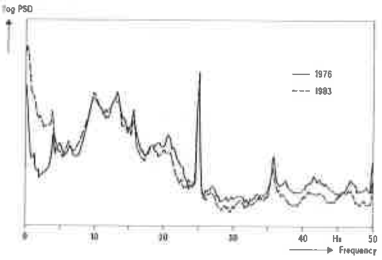

Fig. 6: Influence of time on the vibrations of RPV and RPV internals

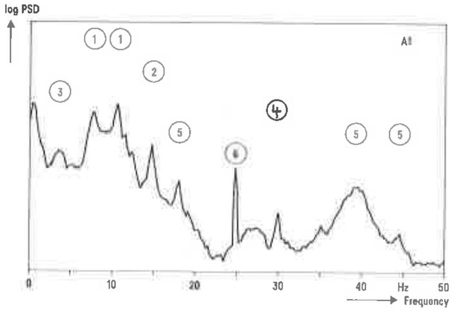

Fig. 7: Typical A-type spectrum

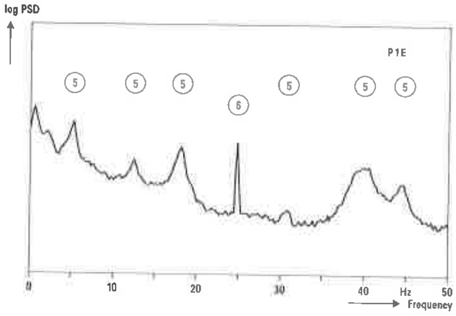

Fig. 8: Typical P-type spectrum

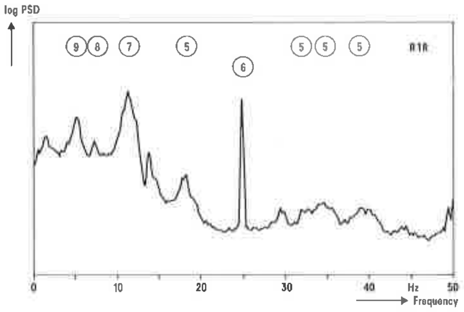

Fig. 9: Typical R-type spectrum

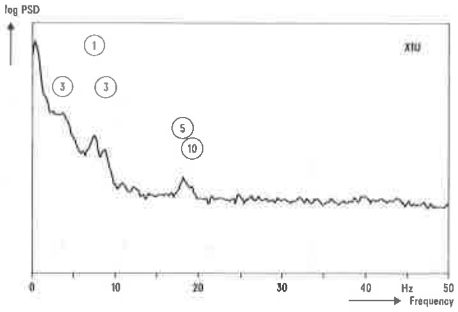

Fig. 10: Typical X-type spectrum

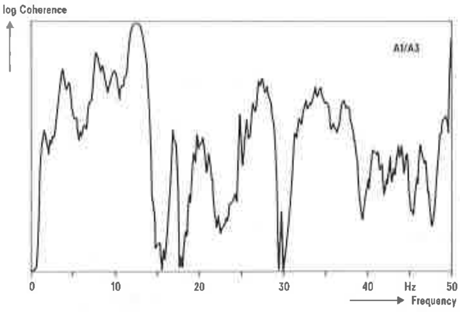

Fig. 11: Coherence of signals of A-type transducer at opposite locations on the RPV lid

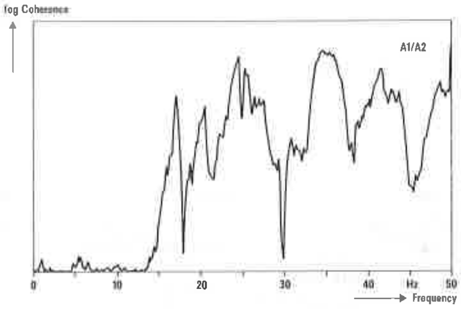

Fig. 12: Coherence of signals of A-type transducers at neighbouring locations

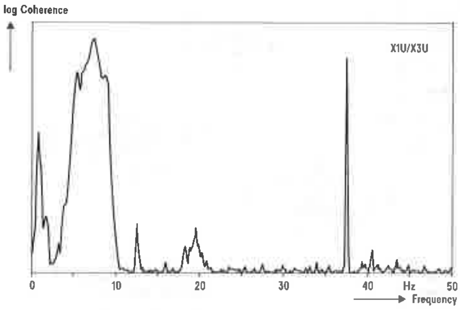

Fig. 13: Coherence of signals of X-type transducers at opposite locations

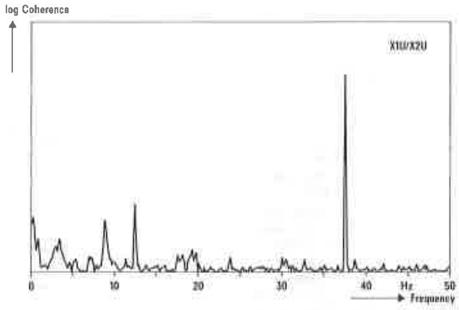

Fig. 14: Coherence of signals of X-type transudcers at neighbouring locations

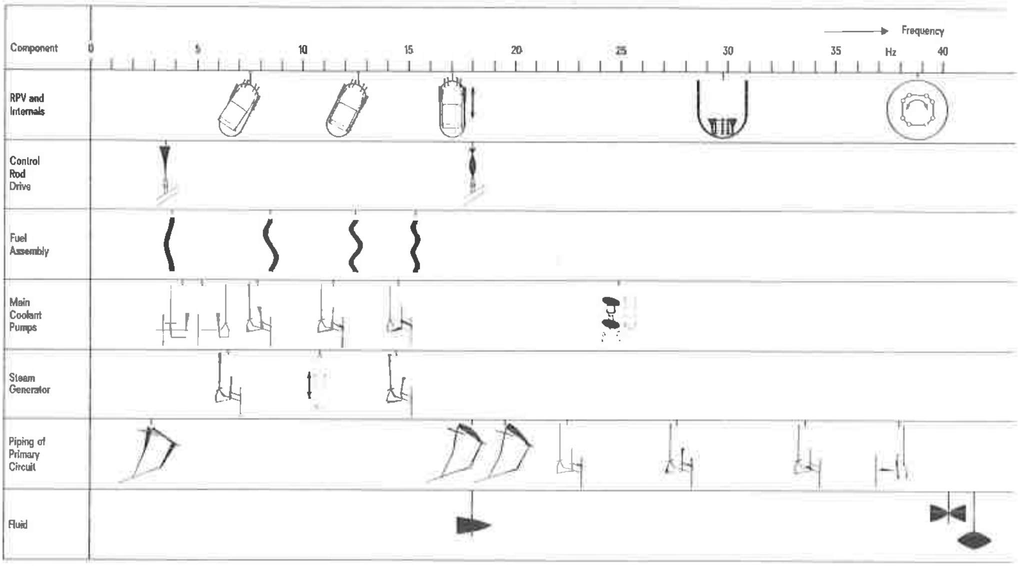

Fig. 15: Typical Eigenforms and Eigenfrequencies of a 1300 MW KWU 4-loop-plant

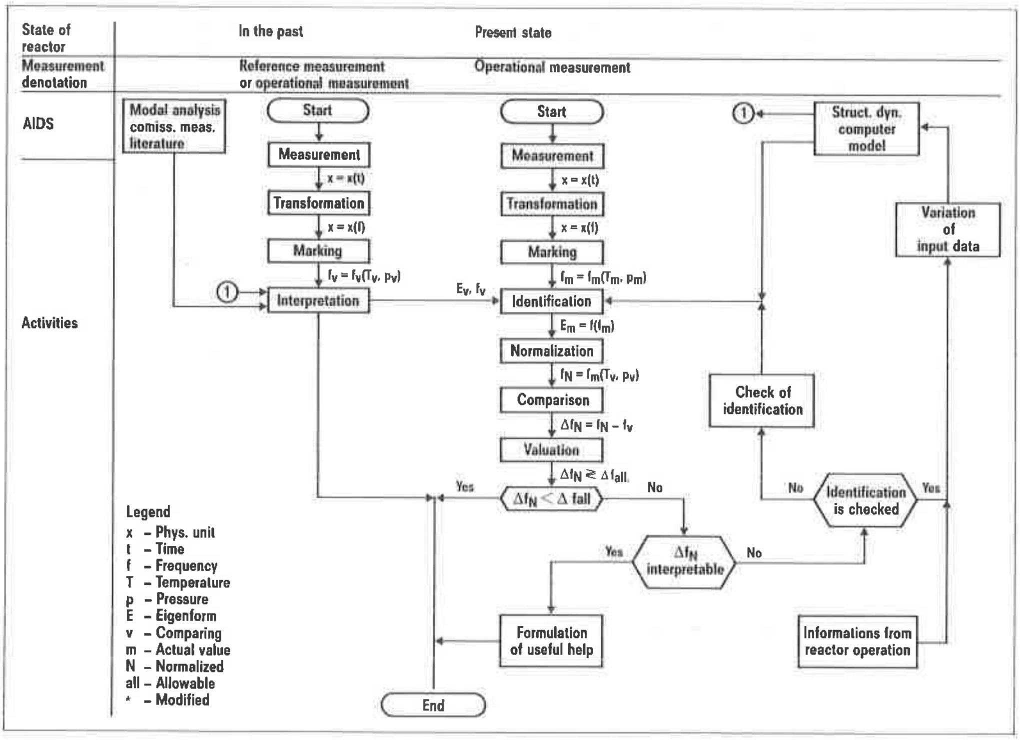

Fig. 16: Flow chart of vibration monitoring working steps