

Vibration Testing and Analysis of Core Barrel Model in Symmetrical/Asymmetrical Liquid Flow Conditions

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ABSTRACT

The paper presents the results of vibration tests of PWR core barrel model, which were performed in liquid flow of hydrodynamic testing circuit in symmetrical/asymmetrical flow conditions simulating 4 and 3 loop operations. The measurements of dynamic stresses and displacements were carried out, processed stochastically and analysed by correlation techniques.

INTRODUCTION

In practical engineering we meet with quite a number of failures occurring in structures exposed to the effects of surrounding fluid flow and caused by the vibrations of aero-hydrodynamic origin. Failures resulting from the mentioned vibrations have made themselves felt as fatigue damages, vibration erosion and corrosion (Sedov et al, 1980 - Malcotsis, 1985 - Koppe et al, 1985) even in nuclear reactors, though particular attention has been given to their operation reliability and safety.

The consequences of accidents caused by vibrations are usually rather serious. The time necessitated by repair amounts up to several weeks, and in some cases up to several years. The resulting costs soar thus very high, and further considerable economic losses are due to the compulsory shut-down throughout the period of repairs. The damages of primary circuit are particularly hazardous, since in the case the risk of radioactive environmental pollution becomes considerable.

The vibrations excited by fluid flow are generally very complex phenomena. Hardly all of them can be theoretically explained in the present-day state of knowledge. This is e. g. true of the dynamic behaviour of core barrel in non-nominal operation resulting from the break-down of one of the circulation pumps. This paper presents the results of model tests of dynamic response of the mentioned reactor component examined under operating conditions of three and four circulation loops.

EXPERIMENTAL EQUIPMENTS

The model of the core barrel of active zone of a PWR reactor is represented in its simplification by a cylindrical thin-walled shell of relative dimensions: $t/a = 0.046$, $a/l = 0.231$ (a ... the radius

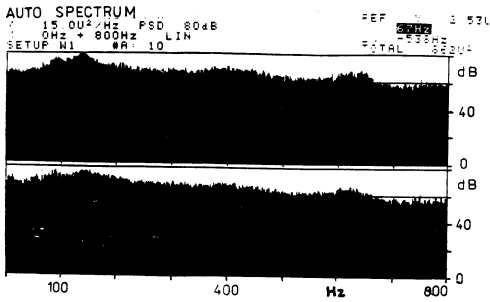


Fig. 1 PSD of stress amplitudes - 3 loops

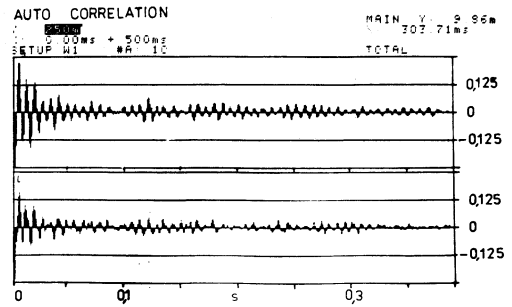


Fig. 2 Autocorrelation of stress amplitudes - 3 loops

of the middle surface, t ... the wall thickness, l ... length). This model was provided with strain and acceleration sensors. There were installed 26 straingages and 7 accelerometers, some of them placed in sections perpendicular to the model axis, others along its creating lines. The core barrel model was placed into a shortened model of the reactor pressure vessel manufactured in the same scale including the distribution of the inlet and outlet branches corresponding to four circulation loops established in the feeding system of the test section. While imitating the operation of three circulation loops, one of the feeding channels was sealed.

DYNAMIC RESPONSE MEASUREMENTS

The measurements of the dynamic stresses and displacements of the core barrel model were carried out in the fluid flow of the hydrodynamic test equipment (Kuželka et al, 1987). It was the so called open operation employing a upper suspended tank. The measuring equipment consisted of the straingage, accelerometric, recording and processing devices. The measurements were performed at different flow rates while the records were taken usually from ten sensors simultaneously. Statistic evaluation of the tape-recorded signals was made in a double-channel B&K 2034 analyser. During the data preparation the signals were tested for stationarity on the basis of standard deviations of the mean square values gained from the equal time intervals of the sample record. To assess the periodicity of the signals, an amplitude probability density function or the autocorrelation function of the signal was applied. The sampling interval of ≈ 0.3125 ms was chosen in connection with the maximum expected frequency up to 800 Hz. The Hanning function within the appropriate frequency interval was used as the weighting function.

Dynamic stresses at three loops

The measurement of dynamic stresses while imitating the operation of the three loops was graphically processed in the forms of the time histories, power spectral densities (PSD), autocorrelograms and probability densities of stress amplitudes. The examples of the results for some places of the model are shown in Figs 1 to 3. The amplitude time histories display a certain growth of the instantaneous amplitude with the increasing flow velocity. The maximum strain amplitude in the circumferential direction reached about 1.10^{-4} , while axially it was less than a half. The PSD of the stra-

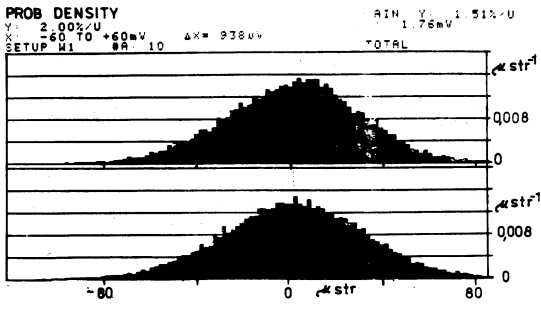


Fig. 3 Probability density of stress amplitudes - 3 loops

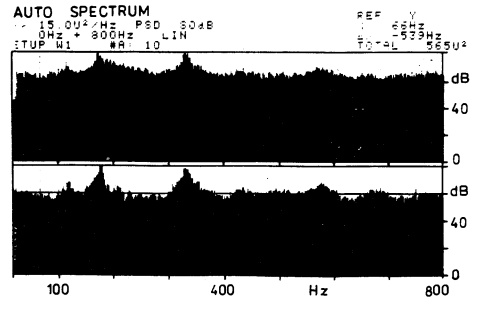


Fig. 4 PSD stress amplitudes - 4 loops

in amplitude (Fig. 1) rose with rising velocity in a similar way. Although the root-mean-square (RMS) value of the hoop stress amplitudes at the mean velocity $v = 8.7 \text{ m.s}^{-1}$ was about 3.3 MPa, the mentioned value measured in axial direction at the same velocity was significantly lower. Figs 2 and 3 give the examples of normalized autocorrelogram and probability density of stress amplitudes obtained from the sensor signals. Their analysis shows that it is a narrow-band random process of non-zero mean square value with a share of hydrodynamic excitation in the response of the core barrel especially in the vicinity of system natural frequencies.

Dynamic stresses at four loops

The measurements of the dynamic stress at four loop operations were processed in the same way as for the three loop operations, i. e. in the forms of time histories, power spectral densities, autocorrelograms and probability densities of the stress amplitudes. For reason of economy, examples are shown only of power spectral density (Fig. 4) and probability density (Fig. 5).

The time histories rescaled a dependence on the mean flow velocity and also the fact that the instantaneous maximum amplitude measured in axial direction is lower than in circumferential one. This was confirmed by processing of the PSD data. While the RMS values of stress amplitudes in circumferential direction at velocity $v = 8.7 \text{ m.s}^{-1}$ reach about 2.6 MPa, the same quantity measured axially is considerably lower. The frequency spectrum of stress amplitudes is rich in clear resonance peaks, whose frequencies largely correspond to same of the natural frequencies of the system: core barrel model - limited fluid surroundings (Kuželka at al, 1983). A thorough analysis of the stress amplitude PSD records of individual sensor will reveal identical frequencies in whose vicinities there are important resonances. Within the band of lower frequencies, the number of the peaks is rather high in the vicinity of 90 Hz, 115 Hz, 176 Hz and 330 Hz. It was confirmed the resonance peak being dependent on the position of the sensor. The records also make evident that frequencies obtained from different sensors in the same frequency band establish a resonance area. This can be explained by limited accuracy of the evaluation process and random character of the investigated phenomena, or by splitting the frequencies of the vibration shapes under consideration. A specimen of the stress amplitude probability density (Fig. 5) points to a narrow-band random process with features similar

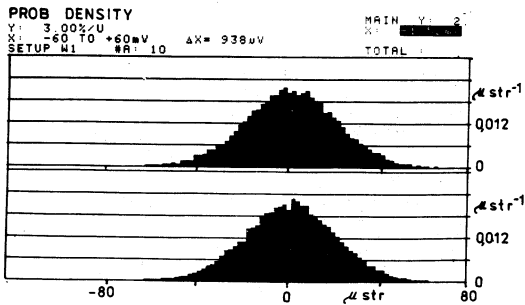


Fig. 5 Probability density of stress amplitudes - 4 loops

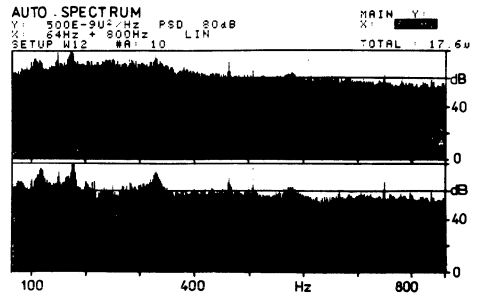


Fig. 6 PSD of displacement amplitudes - 4 loops

to those obtained in the three loop operation.

Dynamic displacements at three loops

The instantaneous displacement amplitudes read in the middle height plane of the model were ranging up to $44 \cdot 10^{-6}$ m. The measured RMS amplitudes reached $6 \cdot 10^{-6}$ m were changing circumferentially. The sensors located on the axial plane of the branches or in the lower half of the model indicated lower RMS values of the displacement amplitudes than those installed on the middle height plane. The frequency spectrum of the displacement amplitudes contains resonance peaks which also appeared in the PSD records of the stress amplitudes. In the frequency region up to 100 Hz, there was a peak within the resonance band around 90 Hz which can be accounted for as a fundamental mode.

Dynamic displacements at four loops

The measured instantaneous amplitudes on the middle height plane of the model ranged up to $26 \cdot 10^{-6}$ m. The RMS values ascertained, they were circumferentially variable and reached $4 \cdot 10^{-6}$ m. The RMS value of displacement amplitudes found on the axial plane of the branches was about $1.5 \cdot 10^{-6}$ m. The frequency spectrum of the displacement amplitudes contains resonance peaks which also appeared in recording of stress when four circulation loops were operating. Besides the peak within resonance band around 90 Hz, they are also the resonance peaks in bands 115 Hz, 175 Hz and 330 Hz (Fig. 6).

ANALYSIS OF RESULTS

The correlation technique was used to analyze the results obtained from two operational states of the core barrel while imitating the function of three and four circulation loops. Fig. 7 shows the recordings of the coherence of displacement amplitudes obtained from the same sensors during operations of three and four loops. When comparing the courses of the displacement coherence from the same pairs of signals, important differences become apparent (Fig. 7). This is also supported by the courses of the stress amplitude coherence for the same pairs of signals under different working conditions. Comparing the coherence curves, it becomes obvious that at three circulation loops operating, the higher coherence tends to occur in the broader frequency interval, while the four

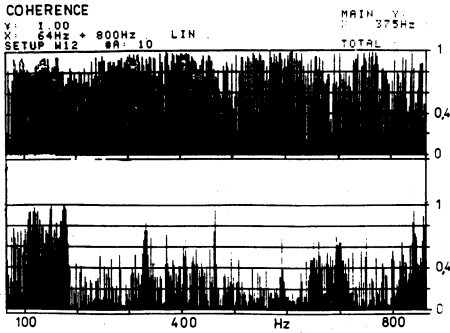


Fig. 7 Coherence of displacement amplitudes - 3 and 4 loops

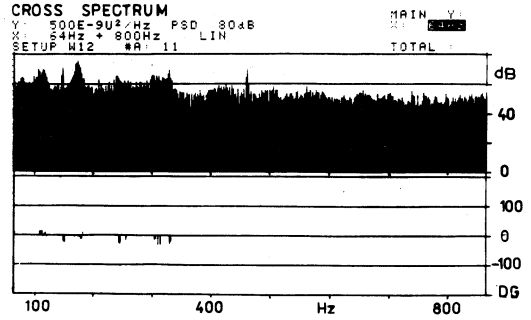


Fig. 8 Cross PSD of displacement amplitudes (ax) - 4 loops

loop operation tends to concentrate the higher coherence in narrower frequency bands. This statement is in a agreement with the fact that the resonance amplitudes of stresses and displacements at three loops are more frequent, higher and clearer then at the four loop operation. An example of the magnitude and phase of the PSD displacement amplitudes for a pair of sensors lying in an axial plane is given in Fig. 8. Obviously, the phases are zero almost along the whole frequency band. The fact is also supported by the recordings of the cross PSD of stress amplitudes obtained from a pair of axial straingages. The implication is that the vibrating random motion of the core barrel model in axial planes occurs so that it can have a beam mode, or it can be a shell vibration of the first axial mode. The cross PSD of the displacement amplitudes, read by a pair of sensors in a vertical plane to model axis, are significantly different from each other. This is also supported by different vibration behaviour of the core barrel as a result of different flow conditions. Reference should be made to phase correlation for characteristic frequencies round 90 Hz, 115 Hz, 176 Hz and 330 Hz.

90 Hz: With three loop operations the phase angle is -155.2 Dg, while with four loops the signals of same pair of sensors yield zero Deg. The vibration antinode planes of the core barrel model, in case of the circumferentially second mode, will thus be oriented for three loops, say, 22.5 Dg \pm 202.5 Dg to axial plane between the inlet branches of the pressure vessel. If there are four loops, the vibration antinode planes will be turned against the previous state and the corresponding orientation will be -22.5 Dg \pm -202.5 Dg.

115 Hz: The phase angle for three loops is -132.4 Dg, while for four loops it is zero Dg. In the vicinity of this characteristic frequency, which corresponds to the third circumferential mode, the spatial orientation of the complex vibration motion of the model is also quite different.

176 Hz: The phase angle of the signals of radially adjacent neighbouring sensors is 158.2 Dg for three loops, while for four loops it is 143.3 Dg.

330 Hz: The signals of sensors at three loop operation are in the phase, while in four loops the phase angle makes 158.8 Dg.

CONCLUSIONS

The tests and measurements of the dynamic response of a core barrel

model in operation conditions of three and four circulation loops have led to the following conclusions:

(1) Asymmetric loading of the core barrel due to coolant fluid flow with only three loop operations leads, in contrast to four loops which are arranged symmetrically, to a higher overall dynamics loads of core barrel.

(2) As a consequence of non-symmetric external forces and of new internal force equilibrium the core barrel changes, in transit from three to four circulation loops, the character of its vibration behaviour which is different from symmetrically distributed inlet flow operation.

(3) In conditions provided by model experiments the random vibration motions of the model were confined to the axially first mode, both for three and four loop operations.

(4) The measured value of the RMS amplitudes of radial displacements at three loops reached $\bar{y} = 6 \cdot 10^{-6} \text{ m}$, while with four loops it was $\bar{y} = 4 \cdot 10^{-6} \text{ m}$.

(5) The values of the RMS stress amplitudes measured in circumferential direction at three loops were 3.3 MPa, while for four loops it reached 2.6 MPa. With respect to the ultimate length of the straingages, on the one hand and the existence of dynamic stress peaks on the other, the values of the actual RMS stress amplitudes will be higher.

(6) The measured RMS stress amplitudes in the axial direction were significantly lower, if it compared with similar values measured circumferentially.

REFERENCES

- Koppe, R. H., Son, E. A. J. and Leshay, D. W. (1985). Nuclear Unit Operating Experiences: 1983 - 1984 Update. EPRI NP-4368, Palo Alto, CA.
- Kuželka, V. and Neuman, F. (1983). The Influence of Thickness and Viscosity of Liquid Annular Layer on Dynamic Behaviour of Cylindrical Shell. Trans. 7th Int. Conf. Structural Mechanics in Reactor Technology, paper B8/11 (North-Holland Publ. Co., Amsterdam), Chicago, U.S.A.
- Kuželka, V. and Vydrař, J. (1987). Hydrodynamic Testing Equipment with Gravitational Channel (in Czech.). Strojirenský zpravodaj, Vol. 3, pp. 23-27.
- Malcotsis, G. (1985). Swiss Experiences in Nuclear Power Plant Operations. Trans. Int. Conf. Operations of Nuclear Power Plants, IAEA, Vienna.
- Sedov, V. K. (1980). Fifteen Years Experiences in Novovoronezh Nuclear Power Plant Operations (in Russian). Elektricheskie stansii, No. 11, pp. 8-12.