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Neutron Noise Analysis for PWR Core Motion Monitoring

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중성자 잡음해석에 의한 PWR 노심 운동상태 감시

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Abstract

Our experience of neutron noise analysis in French-type 900 MWe pressurized water reactor (PWR) is presented. Neutron noise analysis is based on the technique of interpreting the signal fluctuations of ex-core detectors caused by core reactivity changes and neutron attenuation due to lateral core motion. It also provides advantages over deterministic dynamic-testing techniques because existing plant instrumentation can be utilized and normal operation of the plant is not disturbed. The data of this paper were obtained in the ULJIN unit 1 reactor during the start-up test period and the statistical descriptors, useful for our purpose, are power spectral density (PSD), coherence function (CF), and phase difference between detectors. It is found that core support barrel (CSB) motions induced by coolant flow forces and pressure pulsations in a reactor vessel were indentified around 8 Hz of frequency.

요 약

본 논문에서는 불란서에서 건설한 900 MWe 급 가압경수형 원자로의 중성자 잡음해석 결과를 제시하였다. 중성자 잡음해석이란 노심내의 반응도 변화 및 노심의 수평운동으로 인한 노외검출기 신호의 변화를 해석하는 기법을 의미한다. 이러한 방법은 Deterministic Dynamic Testing 기법중에서도 발전소의 정상운전 조건을 유지시키며 기존의 발전소 계측설비를 이용할 수 있다는 장점을 지니고 있다. 본 논문에 사용된 잡음신호는 울진 1호기 원자로의 시운전 시험기간에 구하였으며 이를 통계적 기술함수인 에너지 밀도함수(PSD), 검출기 간의 상관함수 (CF) 및 위상차(Phase Difference)로 나타내었다. 실험결과, 원자로 용기내의 냉각수 흐름 및 압력맥동 등에 의해 유도되는 Core Support Barrel(CSB)의 진동 주파수가 8Hz 근처임을 규명하였다.

1. Introduction

Methodologies for inferring the motion of the reactor core components have been a great concern of the nuclear industries and of the government nuclear agencies in the aspect of safe operation of nuclear power plants. Therefore, many researchers have widely studied for the developement of the core motion monitoring program during reactor operation over the past decades. [1] However, many efforts to clarify the mechanical core dynamics by analytical method have not been progressed until now. On the other hand, the effort to clarify the core dynamics has been studied from noise analysis techniques which are represented as a frequency domain analysis by statistical method.

The first reactor noise analyses were performed by de Hoffman and subsequently by Courant and Wallace. [2,3] these works treated the zero-power reactor neutron density fluctuation. Moore showed that the power spectral densities (PSDs) of the neutron noise induced by reactivity perturbations were proportional to the square of the reactor power.[4] Afterwards, the significant development has been made in the analysis of the neutron noise of reactor. Especially in 1970s, reactor noise analysis techniques were deep engineering interest with an intent to establish the core motion monitoring program of nuclear plant during operation.[5,6] The developement has been accelerated with the aids of developement of computer technologies.

Consequently, most of researches of core motion monitoring program have been recorgniged as a reactor noise analysis technique recently. However, it is not possible to identify the all of the movements of core components completely due to the complexity of configuration of reactor internals. Thus, the purpose of this study is to identify the core support barrel (CSB) motion of ULJIN Unit 1 during steady-state operation and to present the reference data for the future studies.

2. Statistical descriptors for CSB motion

Current signal from the power range flux monitor during steady-state reactor power can be represented as follows;

$$I(t)=I+\sum\delta I(t), \qquad (1)$$

where

I ; steady-state (mean) value of current output
$\sum\delta I(t)$; fluctuating components of current output

The fluctuating components are produced by several driving functions, such as reactivity fluctuations that cause power fluctuations, statistical fluctuations of the reaction rate within the detector, and neutron transmittance variations, between the core and the detector due to core component motions. Because each fluctuating component is small, the reactor system behaves as a linear system, and the principles of superposition is valid.[7,8] If we assume that the statistical fluctuations within the detector can be negligible and the neutron transmittance varitions are dominated by the CSB motion in the low frequency range during steady-state operation, the fluctuating component of the detector can be represented as follows;

$$\sum\delta I(t)\simeq\delta I_C(t)+\delta I_P(t) \qquad (2)$$

where

$\delta I_C(t)$: component induced by CSB motion
$\delta I_P(t)$: component due to reactivity flnctuation in the core.

For our experimental purpose, we introduce the spectral density functions, the auto-power spectral density(PSD) and the cross-power spectral density(C-PSD), from Fourier transform as follows;

$$\begin{aligned}PSD_1(f)&=\langle\delta I_1^*(f)\,\delta I_1(f)\rangle\\&=\langle\delta I_{1C}^*(f)\delta I_{1C}(f)\rangle+\langle\delta I_{1P}^*(f)\,\delta I_{1P}(f)\rangle \qquad (3\text{-A})\end{aligned}$$

$$\begin{aligned}PSD_2(f)&=\langle\delta I_2^*(f)\delta I_2(f)\rangle\\&=\langle\delta I_{2C}^*(f)\,\delta I_{2C}(f)\rangle+\langle\delta I_{2P}^*(f)\,\delta I_{2P}(f)\rangle\\&\qquad (3\text{-B})\end{aligned}$$

$$CSP_{12}(f) = \langle \delta I_1^*(f)\, \delta I_2(f) \rangle$$
$$= \langle \delta I_{1c}^*(f)\, \delta I_{2c}(f) \rangle + \langle \delta I_{1p}^*(f)\, \delta I_{2p}(f) \rangle, \quad (4)$$

where

$\langle \quad \rangle$ stands for ensemble average

Also the coherence function (CF) is introduced, which is commonly used to prove a relationship, such as cause and effect or two effects from a common cause, between two signals.

$$CF_{12} = r^2_{12}(f) = \frac{|CPSD_{12}(f)|^2}{PSD_1(f)\, PSD_2(f)} \quad (5)$$

where CF satisfies the following condition for all frequency:

$$0 \leqq r^2_{12}(f) \leqq 1 \quad (6)$$

Therefore, if there is a frequency range over which most of the signals seen by two detectors are included by a common cause (such as core barrel motion), the coherence can be expected to non-zero over that frequency range.

Hence, the coherence is a crucial statistical parameter for identifying the component induced by CSB motion.

In addition to the coherence, the phase $\phi(f)$ associated with $CPSD_{12}(f)$ is useful for identifying that component of the detector signal induced by CSB motion.

It can be represented as follows;

$$\phi(f) = \tan^{-1}\left\{\frac{Im[CPSD_{12}(f)]}{Re[CPSD_{12}(f)]}\right\} \quad (7)$$

3. Noise data acquisition and analysis results.

Neutron noise recording was performed at 50% power during the start-up test period in the ULJIN unit 1 reactor

Noise data acquisition and analysis instrumentation is shown in Fig 1.

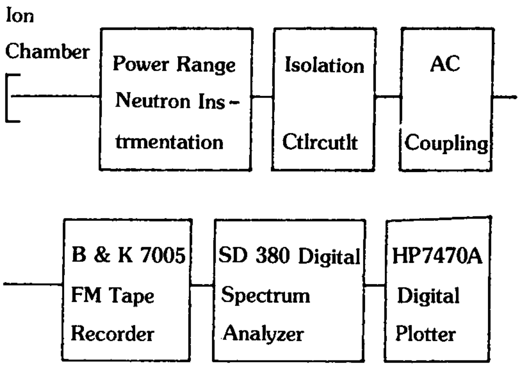

Fig 1. Noise Data Acquisition and Analysis Instrumentation.

Figure 2 shows the relative locations of the ex-core ion chambers used to monitor the core power in the ULJIN unit 1 reactor.[9]

For experimental purpose, analog recordings of neutron noises were transformed to PSD, CF, and phase difference by digital spectrum analyzer in our laboratory, Figure 3 shows an overall view of the PSD transformed from neutron noise signals.

In Figure 3, each PSD shape is very similar over the frequency range of 0~50 Hz. Thus, we can know that PSD does not depend on the detector locations There are several resonance frequencies induced by fluctuation components such as 1 Hz, 8 Hz, 13.5Hz, etc. Our specific concern is to find the exact frequency band of CSB vibration and its moving direction in the ULJIN unit 1 reactor.

Figure 4 and 5 shows the coherence and phase relationship between ex-core detectors. Since it is known that the ex-core detectors are placed at 90° interval, the moving direction of CSB can be estimated.

For example, in the case of the rigid body pendulum motion of CSB, the core will move closer to one(or two) detector(s) while it simultaneously moves away from the opposite detector(s).

Therefore, the phase between detectors on the opposite sides of the core will be ~180°, while signals from detectors at 90° can be in phase or out of phase, depending on the direction of motion.

As it is shown in figure 4 and 5, there are high

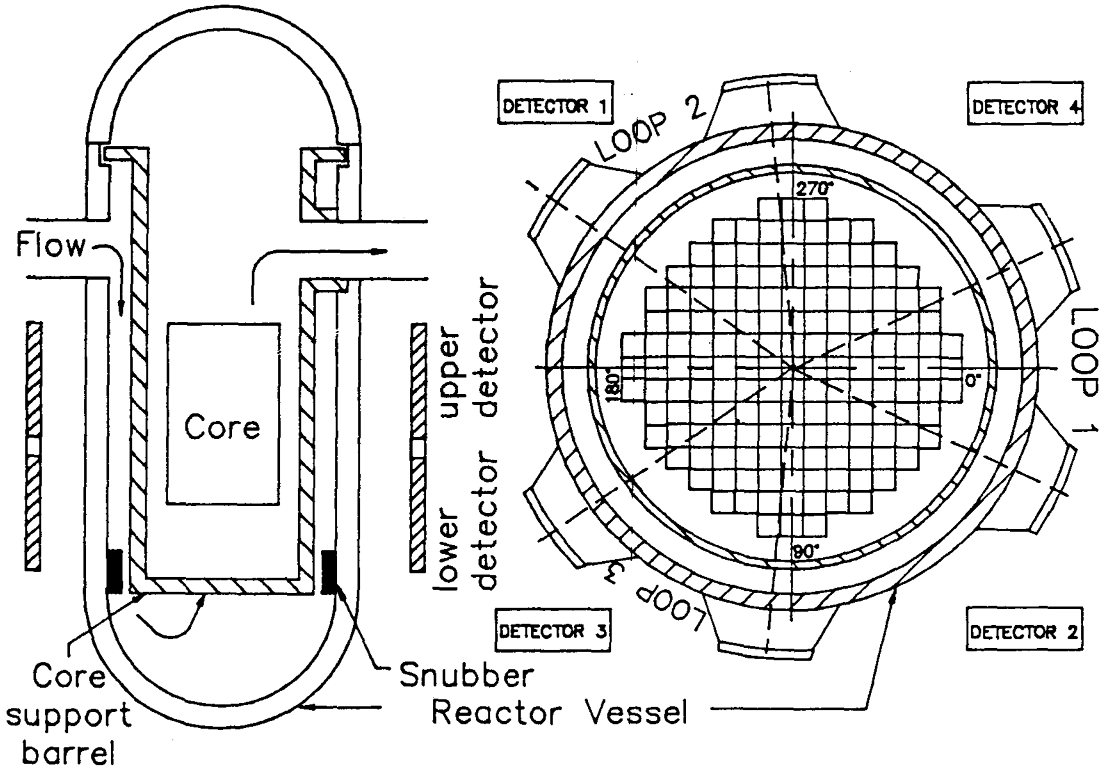

Fig 2. Ex-Core Detector Locations in ULJN Unit 1 Reactor

coherences between opposits detectors (detectors 1 & 2, detectors 3 & 4) over the frequency range of 5~10 Hz and the phase differences are approximately ±180° over this range.

On the other hand, there are moderate coherences between adjoint detectors (detectors 1 & 4, detectors 2 & 3, detectors 2 & 4, detectors 1 & 3).

However, the phase difference is approximately 0° between detectors 1 & 4, detectors 2 & 3 and the phase difference is approximately -180° between detectors 2 & 4, detector 1 & 3.

This phenomenon takes place in the way for both upper detector and lower detector signals. Also it is found that the resonance peaks from the lower detector are slightly higher at the frequency of 8 Hz than those from the upper detector are.

Hence, it can be said that there is a pendular motion of vibration at 8 Hz and the vibration mode is represented as a beam mode vibration like Figure 6, i,e, the dominant directions of vibration are nearly aligned with the across-core detector pairs.

As it is shown in Figure 6, the moving direction may vary at certain conditions such as flow and pressure disturbances but the moving direction is bounded between the quadrantal angle of the core.

4. Conclusions

With the statistical discriptors, PSD, CF and phase difference of ex-core detector signals, the CSB motion of the ULJIN unit 1 reactor is identified. From the present experiment, it is convinced that the neutron noise analysis method will be used to diagnose the reactor core integrity during power operation.

However, the cause of vibration of CSB and environmental effects such as variation of boron concentration and the hardening effect of structure material were not clarified in the experiment.

For their clarification futher analysis and studies should be done.

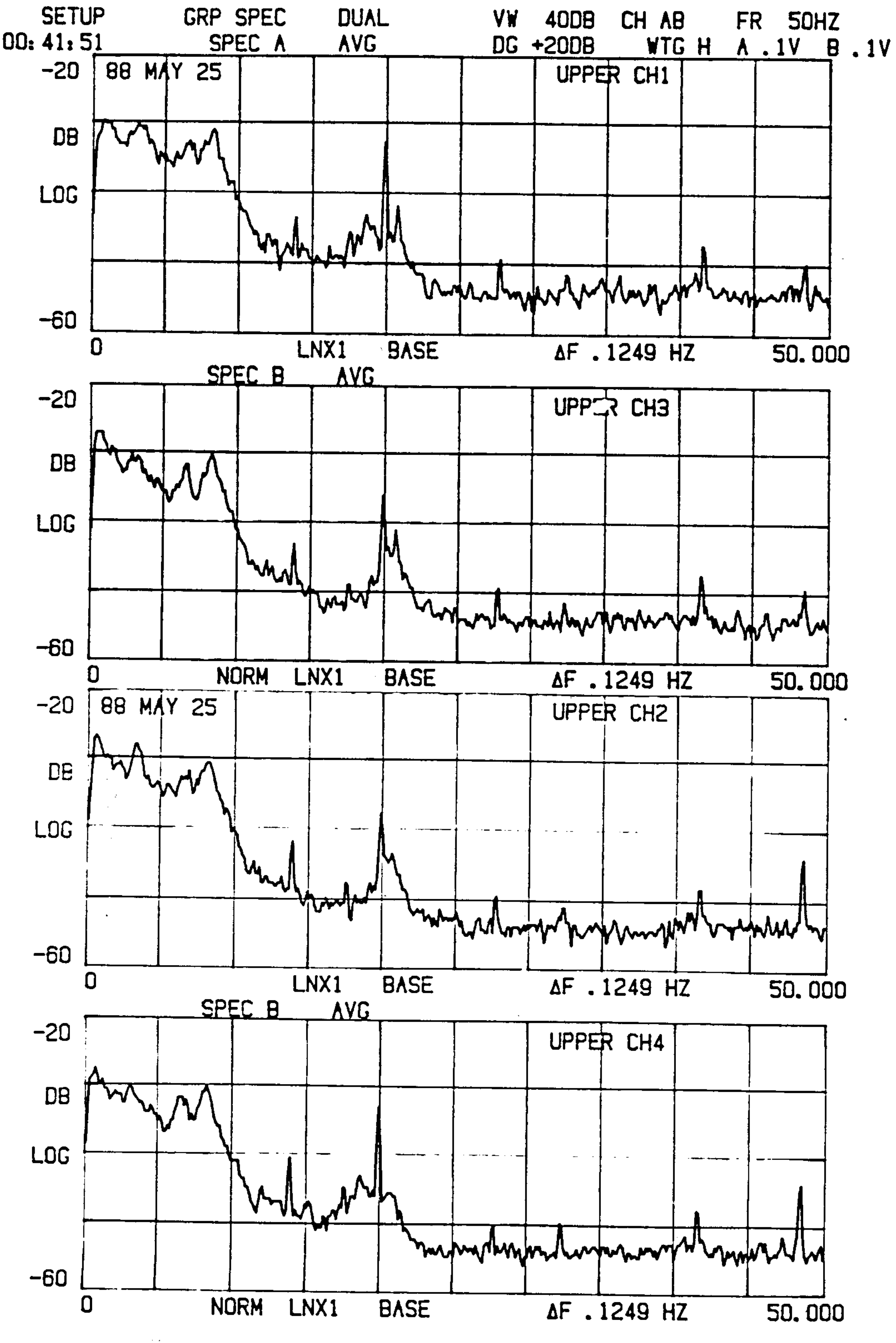

Fig 3-1 PSD of Upper Detector Signals

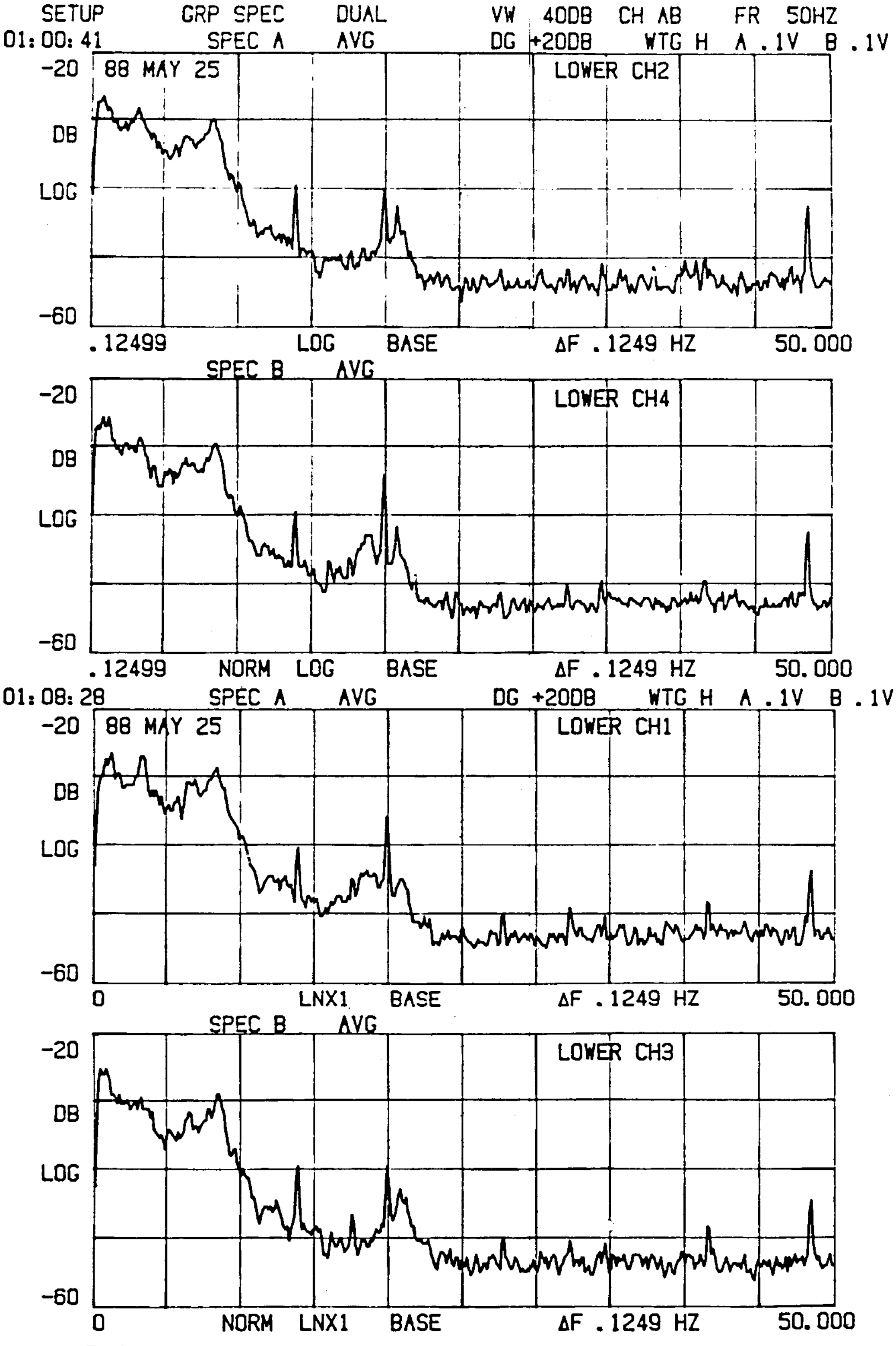

Fig 3-2. PSD of Lower Detector Signals

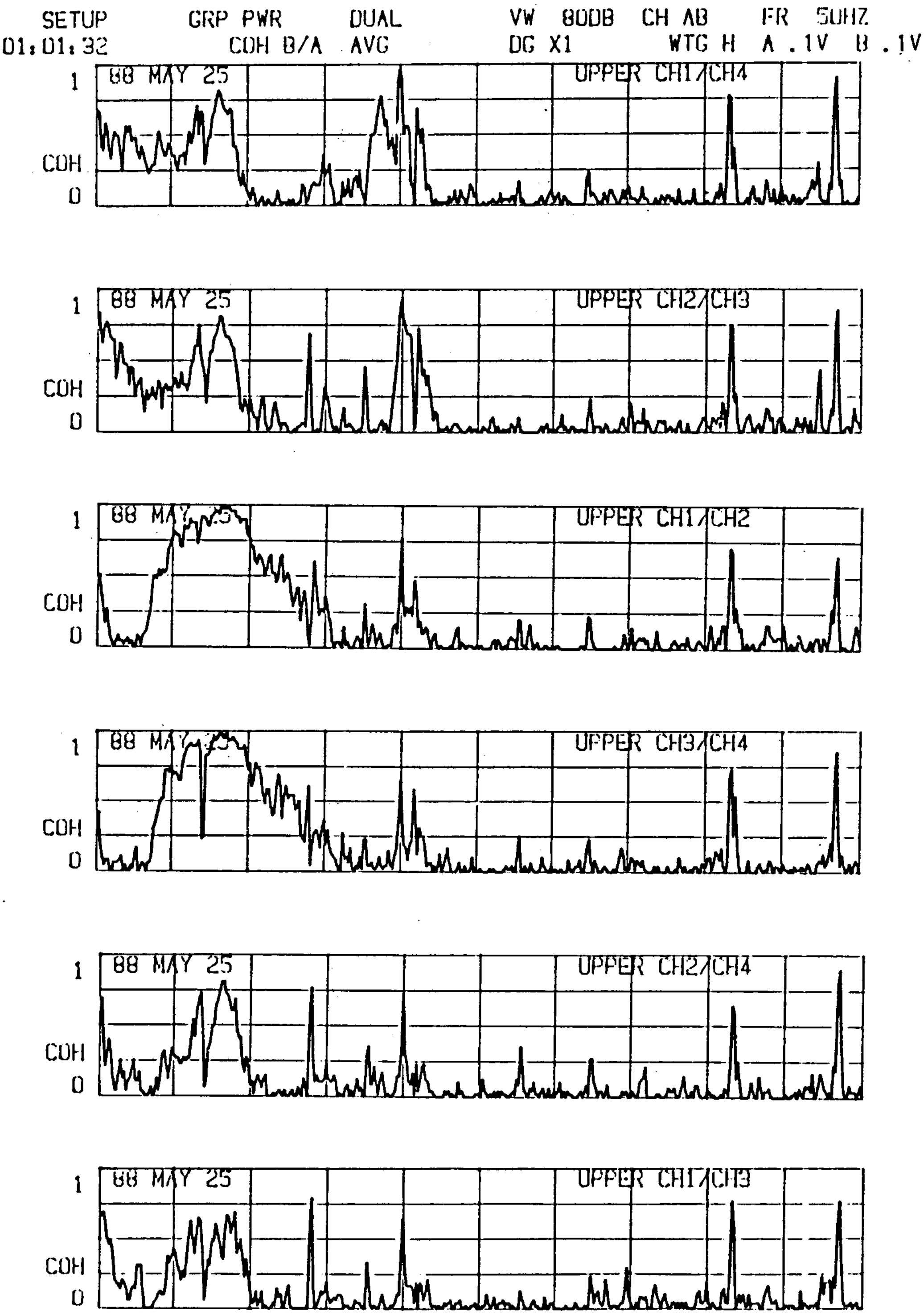

Fig 4-1. Correlation Function between Upper Detector Signals

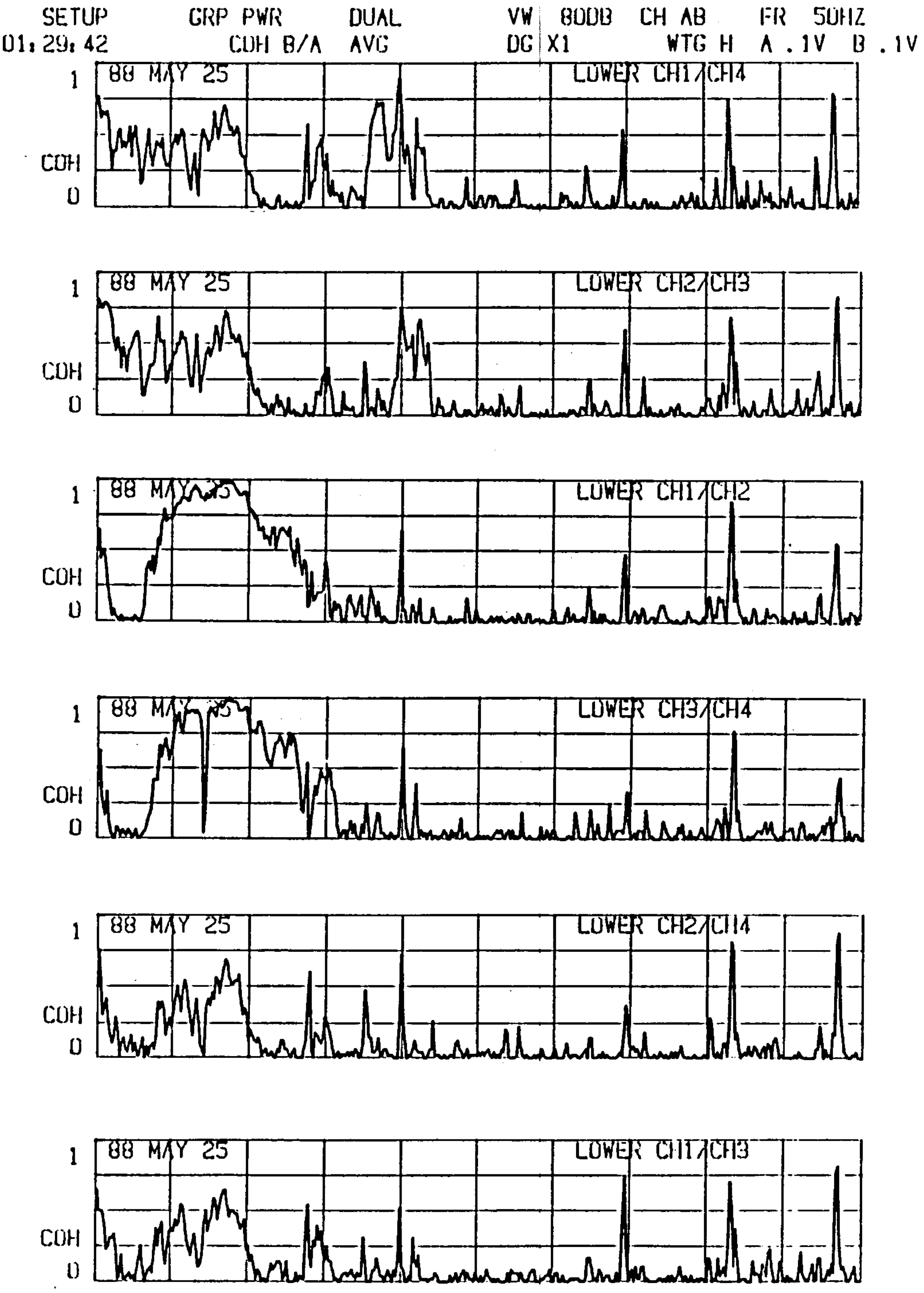

Fig 4-2. Correlation Function between Lower Detector Signals

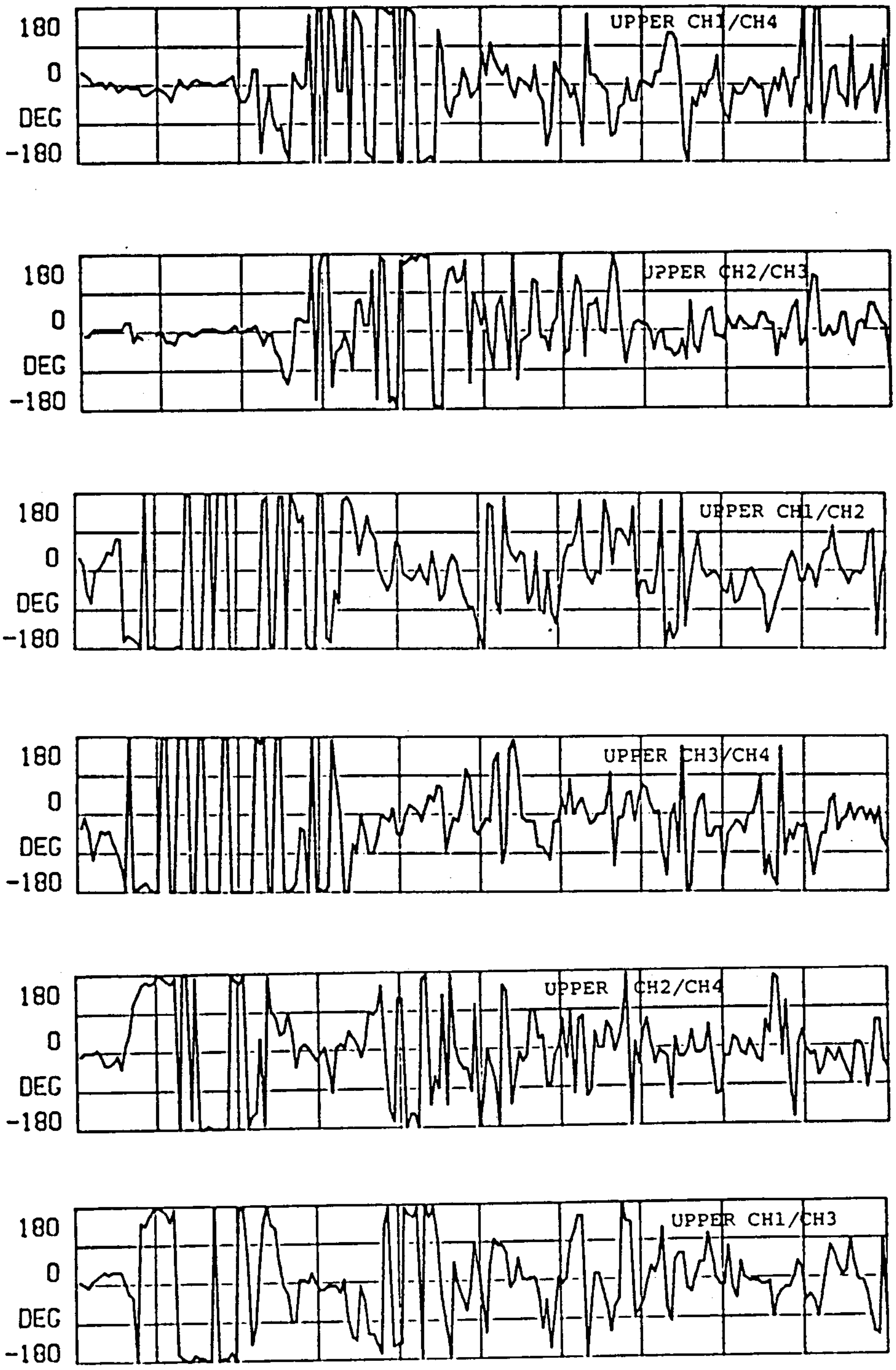

Fig 5-1. **Phase Difference between Upper Detector Signals**

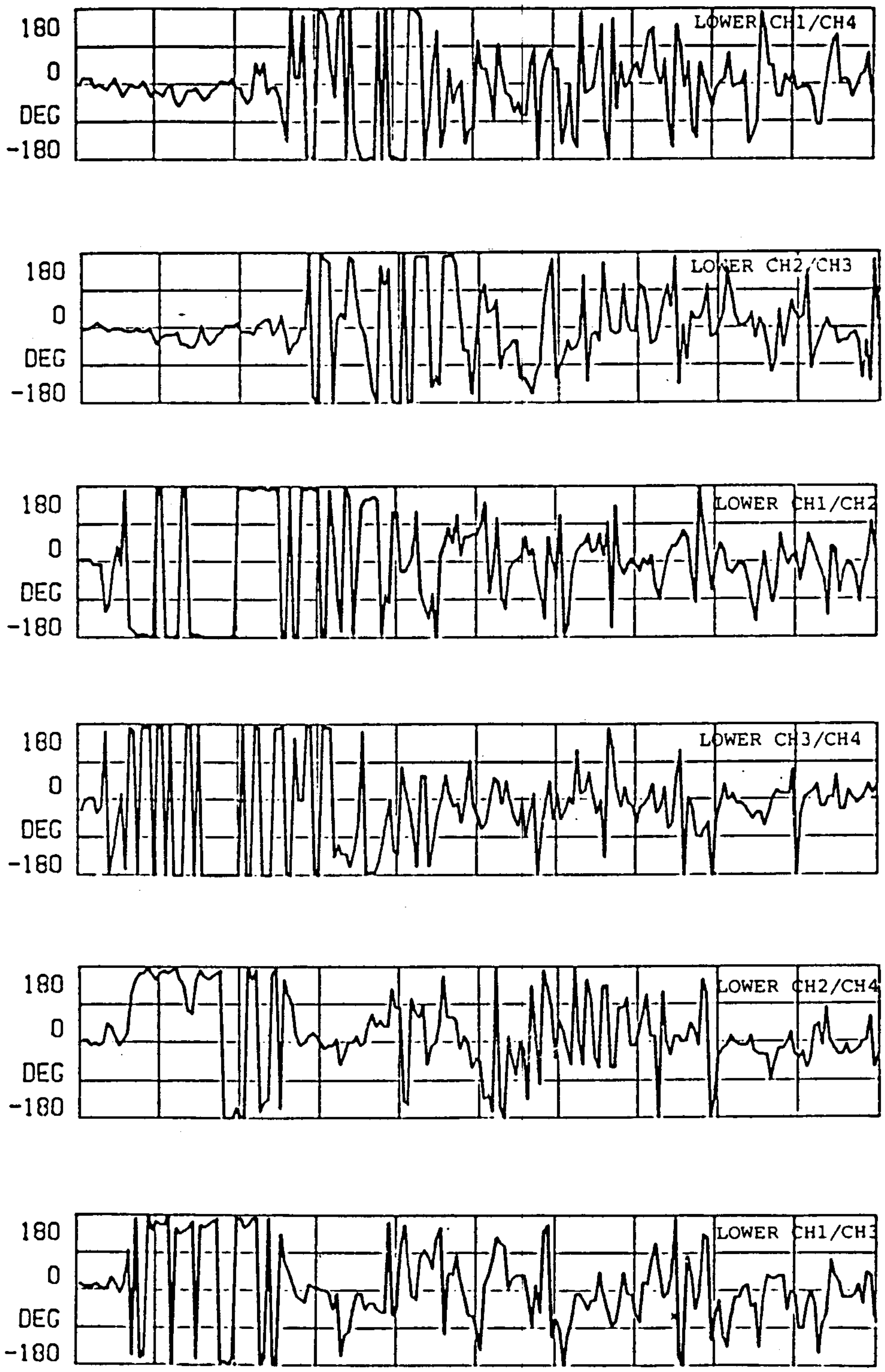

Fig 5-2. Phase Difference between Lower Detector Signals

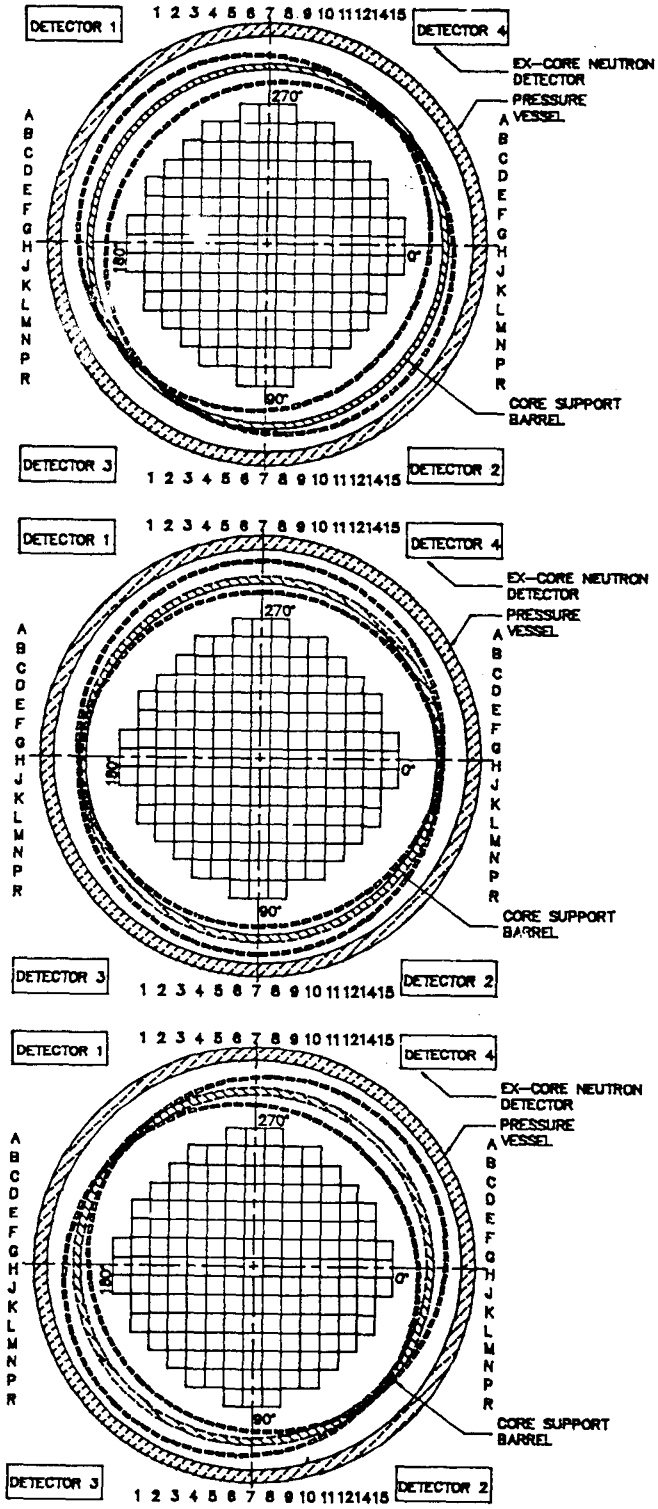

Fig 6. Vibration of CSB in ULJIN Unit 1 Reactor

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