Journal of the Korean Nuclear Society
Volume 29, Number 5, pp. 399~405, October 1997

Phase Separation Algorithm for Ex-core Neutron Signal Analysis

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(Received March 29, 1997)

Abstract

In this study a new phase separated spectral analysis algorithm is proposed to identify CSB vibration mode directly from ex-core neutron signals. Ex-core neutron signals can be decomposed into the global, core support barrel (CSB) beam mode, and CSB shell mode components by the new phase separation algorithm based on the characteristics of Fourier transform.

By using the proposed algorithm and the conventional spectral analysis the vibration mode of the CSB and the fuel assembly of Ulchin-1 NPP were identified from measured ex-core neutron signals.

1. Introduction

The reactor internal structures which consist of many complex components are subjected to flow-induced vibration due to high temperature, high pressure coolant and aging process over reactor life time. These unfavorable effects may cause degradation of structural integrity and result in loosing some mechanical binding components which can impact other equipments and components or cause flow blockage. Therefore it is necessary to monitor and/or diagnose reactor internals for the early detection of their faults or malfunctions.

Every component of reactor internals has its unique vibration behavior. If the structural integrity of reactor internals are degraded or there are mechanical defects on them, their vibration behavior is deviated from normal behavior. The mechanical degradations and defects, therefore, can be detected by analyzing the vibration characteristics of reactor internals that can be identified from measured signals that include the information about them. The change of the vibration characteristics of CSB(core support barrel), especially, is a good index for the fault diagnosis of reactor internals.

Various kind of signals such as ex-core or in-core neutron signals, accereration signals measured at reactor pressure vessel, and reactor coolant inlet or out let pressure signals are used for the vibration analysis of reator internals. Among of them ex-core neutron signals are generally used due to the convenience of measurement. But it is not easy to identify the vibration characteristics of reactor internals from them, because they include several components caused not only by vibration but also by neutronic and hydrodynamic phenomena. The vibration components, however, can be separated from ex-core neutron signals based on the fact that they dominently appear within 2.0~30 Hz, while the frequency band of neutronic and hydrodynamic components is 0.5~2.0 Hz.[1] Besides, by examining the phase characteristics through their cross power spectral densities (CPSD's), the CSB beam modes and CSB shell modes can be identified from several ex-core neutron signals measured via neutron detectors that installed around reactor pressure vessel.[2-3] However, it is a tedious and indirect method to identify them by the conventional spectral analysis.

In this study a new phase separated spectral analysis algorithm is proposed to identify CSB vibration mode directly from ex-core neutron signals. And the vibration mode of the CSB and the fuel assembly of Ulchin-1 NPP are identified from the ex-core neutron signals by using the proposed algorithm and the conventional spectral analysis. Finally the identified vibration modes are compared with those of Tricastin-1 that is the prototype of Ulchin-1.

2. Phase Characteristics of Neutron Signals

The DC component of ex-core neutron signal is used to monitor reator power, but its AC component normally regarded as power fluctuations includes the reactor dynamic information such as reactor internal vibrations, reactivity variations, and hydrodynamic phenonena. To identify the reactor internal vibration mode from the ex-core neutron signals measured through 4 neutron detectors that installed around reactor pressure vessel, we utilize the phase characteristics between them as follows[2-3]:

- Global components due to reactivity variation
  - The phase between all signals is in-phase.
- Vibration components due to CSB beam mode
  - The phase between two neighbering signals is in-phase or out-of-phase according to the movement direction.
  - The phase between two opposite signals is out-of-phase.
- Vibration component due to CSB shell mode
  - The phase between two neighbering signals is out-of-phase.
  - The phase between two opposite signals is in-phase.

3. Separation of the In-phase and Out-of-phase Signal Components

Phase between two signals can be examined through their CPSD. But they give only the phase information, not the degree of contribution of each components. If the in-phase and out-of phase components be separated and thus their contribution be identified, it will be very helpful for the vibration analysis and the fault diagnostics of reactor internals.

Mayo[4] proposed a method to separate the in-phase and out-of-phase PSD's for two signals us-

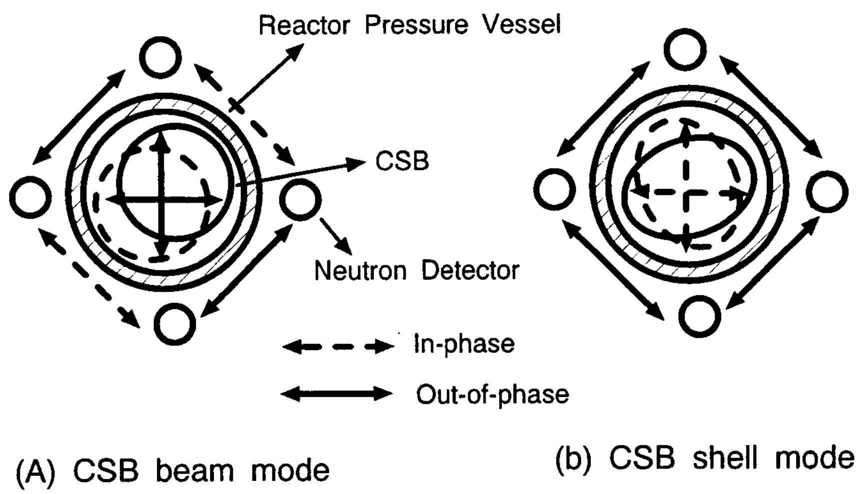

Fig. 1. Phase Characteristics According to CSB Vibration Mode

ing their APSD's, CPSD's and coherence. However, his method requires calculation of CPSD's and coherence, and has some difficulties in applying to the situation containing more than 2 signals.

In this study, a new algorithm utilizing Fourier transform characteristics without calculating CPSD's and coherence is proposed. This algorithm can reduce the number of computations and is easily applicable to more than 2 signals.

Let two signals s1(t) and $s_2(t)$ contain the in-phase component x(t) and out-of-phase y(t) such as,

$$s_1(t) = x(t) + y(t) \quad (1)$$

$$s_1(t) = x(t) - y(t) \quad (2)$$

Define a complex variable z(t) as,

$$z(t) = s_1(t) + j\, s_2(t) \quad (3)$$

and take Fourier transform of z(t),

$$F[z(t)] = Z(f).Re + j\, Z(f).Im \quad (4)$$

where $Z(f).Re = X(f).Re - X(f).Im + Y(f).Re + Y(f).Im$

$Z(f).Im = X(f).Re + X(f).Im - Y(f).Re + Y(f).Im$

and Z(f).*Re* and Z(f).*Im* mean the real part and imaginary part of Z(f), respectively.

Using the property that the real part of Fourier transform of a real function is an even function and the imaginary part is an odd function,[5] the in-phase and out-of-phase component can be easily separated as follows :

$$X(f).Re = 1/4\{Z(f).Re + Z(f).Im + Z(-f).Re + Z(-f).Im\} \quad (5)$$

$$X(f).Im = 1/4\{-Z(f).Re + Z(f).Im + Z(-f).Re - Z(-f).Im\} \quad (6)$$

$$Y(f).Re = 1/4\{Z(f).Re - Z(f).Im + Z(-f).Re - Z(-f).Im\} \quad (7)$$

$$X(f).Im = 1/4\{Z(f).Re + Z(f).Im + Z(-f).Re + Z(-f).Im\} \quad (8)$$

Then the in-phase PSD and out-of-phase PSD can be calculated as

$$P_{xx}(f) = E\,[X(f).Re^2 + X(f).Im^2] \quad (9)$$

$$P_{yy}(f) = E\,[Y(f).Re^2 + Y(f).Im^2] \quad (10)$$

where E[·] is the expectation operator, and $P_{xx}(f)$ and $P_{yy}(f)$ are PSD's of in-phase and out-of-phase component, respectively.

Fig. 2 and 3 show the comparison of in- and out-of-phase PSD calculated by our algorithm and Mayo's.

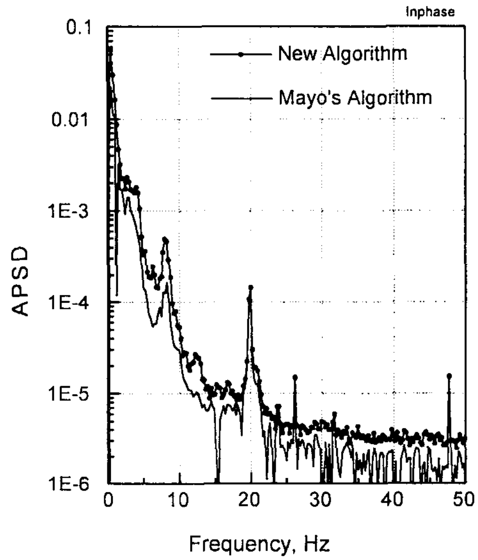

Fig. 2. In-Phase APSD of 2 Neutron Signals

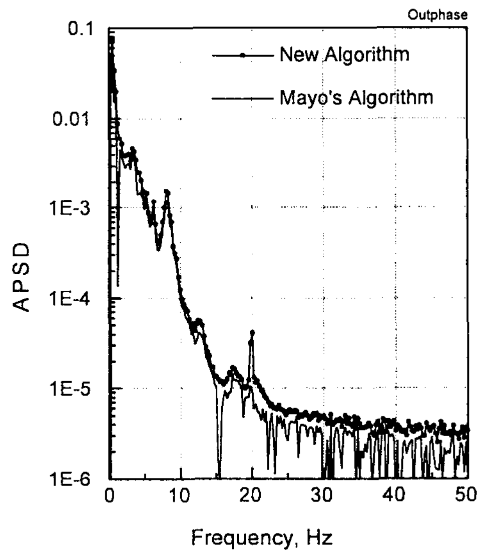

Fig. 3. Out-of-Phase APSD of 2 Neutron Signals

Now let's apply the new algorithm to 4 neutron noise signals. Let $x_1(t)$, $x_2(t)$, $y_1(t)$, and $y_2(t)$ be 4 neutron signals from 4 neutron detectors and be composed of 4 phase components, $g(t)$, $s(t)$, $b_1(t)$, and $b_2(t)$, that is, the global mode (in-phase in all direction), shell mode, two perpendicular beam modes. The phases between the neutron signals corresponding to the each components are shown in Fig. 4.

$$x_1(t) = g(t) + s(t) + b_1(t) + b_2(t) \qquad (11)$$

$$x_2(t) = g(t) + s(t) - b_1(t) - b_2(t) \qquad (12)$$

$$y_1(t) = g(t) - s(t) + b_1(t) - b_2(t) \qquad (13)$$

$$y_2(t) = g(t) - s(t) - b_1(t) + b_2(t) \qquad (14)$$

Defining two complex variables $z_1(t)$ and $z_2(t)$ again as ;

$$z_1(t) = x_1(t) + j\, y_1(t) \qquad (15)$$

$$z_2(t) = x_2(t) + j\, y_2(t) \qquad (16)$$

and applying the same procedure as in the case of two signals, we can easily obtain the Fourier transformed components as follows ;

$$G(f).Re = 1/8\{Z_1(f).Re + Z_1(f).Im + Z_1(-f).Re + Z_1(-f).Im + Z_2(f).Re + Z_2(f).Im + Z_2(-f).Re + Z_2(-f).Im\} \qquad (17)$$

$$G(f).Im = 1/8\{-Z_1(f).Re + Z_1(f).Im + Z_1(-f).Re - Z_1(-f).Im\} - Z_2(f).Re + Z_2(f).Im + Z_2(-f).Re - Z_2(-f).Im\} \qquad (18)$$

$$S(f).Re = 1/8\{Z_1(f).Re - Z_1(f).Im + Z_1(-f).Re - Z_1(-f).Im\} + Z_2(f).Re - Z_2(f).Im + Z_2(-f).Re - Z_2(-f).Im\} \qquad (19)$$

$$S(f).Im = 1/8\{Z_1(f).Re + Z_1(f).Im - Z_1(-f).Re - Z_1(-f).Im\} + Z_2(f).Re + Z_2(f).Im - Z_2(-f).Re - Z_2(-f).Im\} \qquad (20)$$

$$B_1(f).Re = 1/8\{Z_1(f).Re + Z_1(f).Im + Z_1(-f).Re + Z_1(-f).Im\} - Z_2(f).Re - Z_2(f).Im - Z_2(-f).Re - Z_2(-f).Im\} \qquad (21)$$

$$B_1(f).Im = 1/8\{-Z_1(f).Re + Z_1(f).Im + Z_1(-f).Re - Z_1(-f).Im\} + Z_2(f).Re - Z_2(f).Im - Z_2(-f).Re + Z_2(-f).Im\} \qquad (22)$$

$$B_2(f).Re = 1/8\{Z_1(f).Re - Z_1(f).Im + Z_1(-f).Re - Z_1(-f).Im\} - Z_2(f).Re + Z_2(f).Im - Z_2(-f).Re + Z_2(-f).Im\} \qquad (23)$$

$$B_2(f).Im = 1/8\{Z_1(f).Re + Z_1(f).Im - Z_1(-f).Re - Z_1(-f).Im\} - Z_2(f).Re - Z_2(f).Im + Z_2(-f).Re + Z_2(-f).Im\} \qquad (24)$$

Then each phase PSD components can be computed as,

$$P_{gg}(f) = E[G(f).Re^2 + G(f).Im^2] \qquad (25)$$

$$P_{ss}(f) = E[S(f).Re^2 + S(f).Im^2] \qquad (26)$$

$$P_{b1b1}(f) = E[B_1(f).Re^2 + B_1(f).Im^2] \qquad (27)$$

$$P_{b2b2}(f) = E[B_2(f).Re^2 + B_2(f).Im^1] \qquad (28)$$

where $P_{gg}(f)$, $P_{ss}(f)$, $P_{b1b1}(f)$, and $P_{b2b2}(f)$ are PSD's of global, shell mode vibration, and two perpendicular beam mode vibration components, respectively.

4. The Analysis Result of Neutron Signals of Ulchin-1 NPP

Ulchin-1 NPP, which is a 900 MWe 3-loop PWR (Pressurized Water Reactor), is now loaded with 8th fuel cycle since its commercial operation started in 1988. The ex-core neutron detectors are installed at

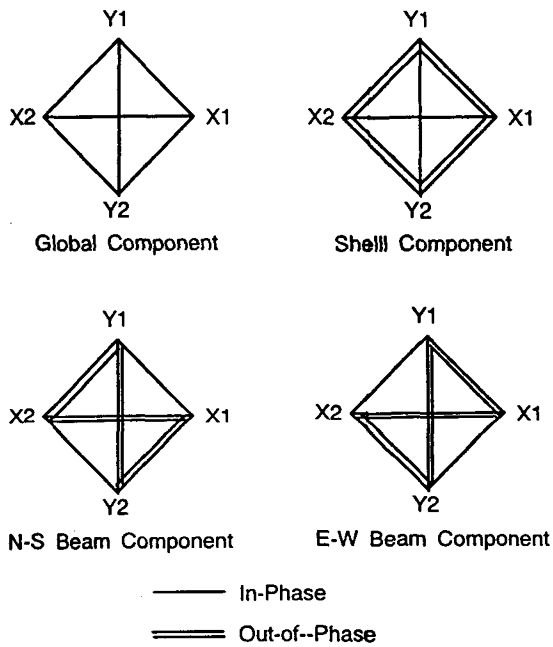

Fig. 4. Phase Characteristics of Each Phase Separated Components

the upper and lower elevation at 90° intervals around the reactor vessel as shown Fig. 5.

The measured neutron signals were analyzed to identify the vibration characteristics of the Ulchin-1 reactor internals by the conventional spectral analysis method and our proposed phase-separated spectral analysis method.

Fig. 6 represents the APSD's of neutron signals from the bottom 4 neutron detectors. It is found in Fig. 6 that APSD values of N1 and N4 are different from those of N2 and N3. The difference is thought to come from the thermal shield partially installed around the CSB. This is confirmed from the upper 4 channel measurements, N6~N8. There are several frequency peaks in Fig. 6, each of which corresponds to a certain physical phenamenon (particularly vibration in this case). But it is hard to identify which peak corresponds to what physical phenomenon.

Fig. 7 show the separated 4 phase components APSD's computed by the proposed algorithm for N1~N4. It is shown in Fig. 7 that the beam modes appear stronger than the other phase components in the frequency range of 2~10 Hz, the shell mode does around 20Hz and the global mode does in 0~2Hz and 12~18 Hz. It is obvious from Fig. 7 that the peak of 8.2 Hz corresponds to the beam mode vibration of CSB, 20.6 Hz to the shell mode vibration of CSB.

Because the first frequency of PWR's fuel assembly generally shows a broad peak in 2~5 Hz and its phase characteristic is similar to the CSB beam mode,[1] 3 Hz is thought to be the first vibration frequencies of fuel assembly. The small peak at 6.2 Hz is the second vibration frequency or the second harmonics of fuel assembly. 8.2 Hz and 20.6 Hz are identified as the beam and shell mode frequencies of CSB, respectively, on the base of the phase separation results. These results show excellent agreement with the vibrational characteristics of Tricastin-1 which is the prototype of Ulchin-1[6] as shown in Table 1. The identified beam mode frequency are also agree with the result of the reference[7] in that 8 Hz is identified as beam mode frequency. The frequency of 19.9 Hz is identified as the rotational speed (1192 rpm) of reactor coolant pump, not the structural natural vibration component. These results are verified by the finite element analysis in our another paper. [8]

The peaks in 12~18 Hz could not be identified in this study, but from their global phase characteristics they are thought to be acoustic resonances or up and down motion components of the reactor vessel.

As described above, the phase separated APSD reveals the phase characteristics between signals more clearly than the conventional APSD or CPSD, and from which the dominant frequency band of each signal component can be easily found.With this result, it is possible to monitor a certain narrow band frequency and to early detect the faults occurred in reactor internals due to flow-induced vibration. For example, the APSD of CSB beam mode components are more sensitively changed than those of the CSB shell mode components in case that CSB hold-down springs are defected, while the characteristics is reverse in case that the structural integrity between CSB and core baffle plate is weak. It is very helpful for the vibration analysis and the fault diagnostics of reactor internals.

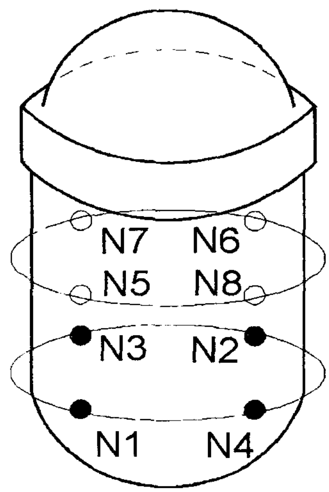

Fig. 5. Location of Ex-Core Neutron Detectors in Ulchin-1 NPP

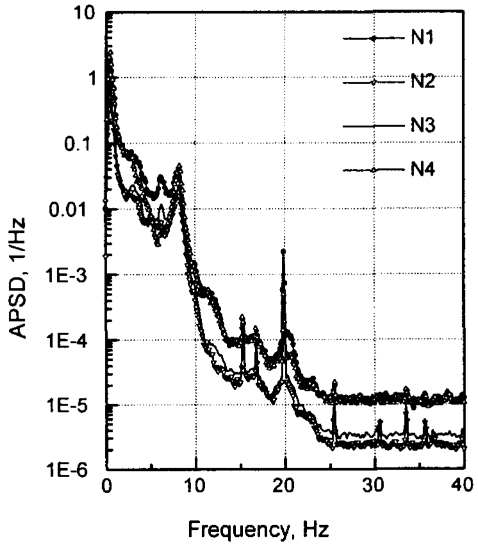

Fig. 6. APSD of Neutron Signals, N_1-N_4

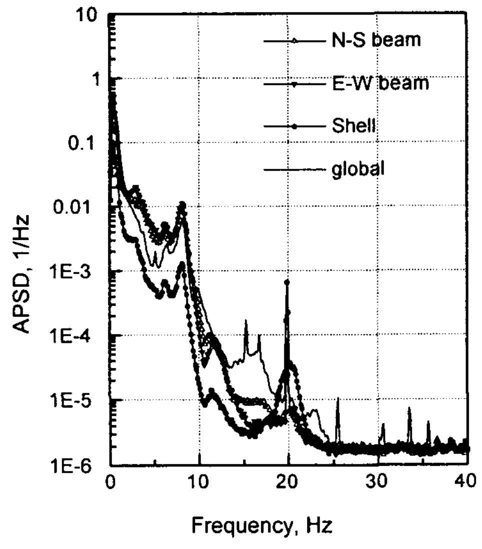

Fig. 7. Phase Separated APSD of Neutron Signals, N_1-N_4

5. Conclusions

For the vibration analysis and the fault diagnostics of reactor internals, a new phase seperated spectral analysis algorithm is proposed to identify CSB vibration mode directly from ex-core neutron signals. This algorithm can reduce the number of computations and is easily applicable to more than 2 signals. The phase separated spectral analysis can be a very helpful tool for the vibration analysis and the fault diagnostics of reactor internals.

Table. 1. Comparision of Vibration Resonance Frequencies Between Tricastin-1 NPP and Ulchin-1 NPP

Reactor Internals	Vibration mode	Tricastin-1	Ulchin-1
Fuel Assembly	1st mode	3.2	3
	2nd mode	6.0	6.2
Core Support Barrel	1st beam mode	8.2	8.2
	1st shell mode	20.0	20.6

By using the proposed spectral analysis method, the CSB beam and shell mode frequenies of Ulchin-1 NPP are identified from measured neutron signals as follows :

- the 1st fuel assembly vibration frequency : 3 Hz
- the CSB beam mode vibration frequency : 8.2 Hz
- the CSB shell mode vibration frequency : 20.6 Hz

These identified frequencies show excellent agreement with the vibrational characteristics of Tricastin-1 which is the prototype of Ulchin-1.

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