Feasibility Study of Noise Analysis Techniques for Estimating Reactivity Coefficient in a BWR

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The reactivity coefficient with respect to void, pressure, fuel temperature, moderator temperature, etc. is an important parameter used for reactor safety calculations. But no effective method has been available for measuring each reactivity coefficient in operating BWR plants except for moderator temperature coefficient.

This paper presents a method for reactivity coefficient estimation using noise analysis. The basic idea consists of combining the process-to-reactor-power dynamics model estimated by noise analysis and a theoretical model for the reactor kinetics. Noise analysis has been carried out for BWRs of different type, i.e. BWR-4, -5 and ABWR. The application of noise analysis to the reactivity coefficient estimation requires sufficient correlation with signal causality from the process variable to reactor power. Through the noise analysis using coherence analysis and signal transmission path analysis, it has been indicated that different reactivity coefficients can be estimated in different BWR plants, i.e. such reactivity coefficient as pressure variation in a BWR4 and an ABWR, coolant flow variation in an ABWR and so forth.

The pressure coefficient estimated by the present method has been compared with the void coefficient estimated using a core calculation code for the corresponding core condition as that when the noise signals were recorded. As the result it was found that the both results were very similar in behavior with the correlation coefficient of ~0.77, i.e. slowly increasing tendency towards the end of cycle. The current state of the art in the method development is that the results are valid in terms of relative trend estimation.

The result of the present study suggests the feasibility of the noise analysis technique as a tool for tracking the reactivity coefficient during reactor operation. This may open the possibility in the future for an on-line monitoring of an advanced core with new type of fuels, such as MOx fuels and very high burn-up fuels, etc, as well as for validating a computer code used for safety analysis and in-core management.

KEYWORDS: Noise analysis, Parameter estimation, Reactivity coefficient, Diagnosis, Reactor safety

I. Introduction

The solid development of nuclear technology in the last decades has brought about higher reliability and performance in the reactor operation. Towards future further improvement of reactor operations are expected by introducing more advanced core designs with very high burn-up fuels, MOx fuels, power uprating etc.

In order to maintain the high level of reactor safety as well as operational economy, it will become more important in the future to get detailed information of the core state during reactor operation. Among others the reactivity coefficient (RC) is an important parameter. Its measurement, if available, will be very valuable for validating the core design and analysis codes as well as for detecting an unforeseen occurrence at its early stage if it should have taken place.

In PWRs the moderator temperature coefficient of reactivity (MTC) has been taken up as an important safety parameter. In some countries it is required to measure the MTC during the cycle.

In BWRs the RCs for void, fuel temperature, moderator temperature and pressure are important parameters. Among these the void has the most significant effect on the reactivity. It has strong negative feedback effect. But its value depends mainly on loaded fuels and core design but not on the burn-up like the MTC in PWRs. Accordingly it has been taken as the design parameter to be determined by code calculations and the value has not been checked by the measurement. However this does not mean that the measurement of RC is not interesting in BWRs. Instead it is very important since the void coefficient may vary significantly depending on the reactor operational condition.

Concerning the measurement of RC, no effective method has been available in operating BWRs except for the MTC.

An empirical method for the RC estimation has been developed by combining noise analysis and the point reactor kinetics model. In the noise analysis one utilizes process fluctuations that take place during plant operation. If the process fluctuations of a variable give significant influence on the neutron flux, the transfer function (TF) between them can be estimated by applying the noise analysis. Then the RC for the process variable can be deduced by eliminating, from the estimated TF, the factor due to reactor kinetics.

One advantage of applying the noise analysis is that process noise signals may be recorded at any time, using a
transient recorder installed at a BWR, during the plant operation without giving any disturbances. This allows collecting the information on the RC over wide operational range.

Another advantage of the noise analysis approach is the ease of implementation. For example, the RC may be estimated with the aid of a core simulator, where one best adjusts the reactivity, and hence the RC, so as to minimize the difference of the measured reactor power and its estimate by the simulator using measured process values as the boundary condition. However, the application of the simulator may require much effort for parameter tunings specific to each core and/or reactor. Compared with this the noise analysis method adopts the same signal analysis procedure and same kinetics model. Accordingly the implementation becomes simple and general, allowing its application to any BWRs with only a few parameter tunings.

There are two major problems in the application of noise analysis to the RC estimation. The first problem is a possible bias in the TF estimate due to the so-called measurement noise in the recorded signals. As explained in the next section, the value of RC is deduced from the gain of TF between the process variable and neutron flux. It is known that the estimated gain may get biased if the measured signals are contaminated by additional noise. Normally it is not known how much the signals are contaminated by the measurement noise. One possible method to alleviate this is to apply the coherence analysis if multiple signals are available either or both of signals of process variable and neutron flux. Then one can estimate the bias to be compensated for from the gain estimate.

The second problem is the so-called the condition of causality in signal fluctuations. In a BWR the major source of process fluctuations is due to boiling process in the core coolant. It affects the core and process variables via complicated feedback loops in BWR dynamics. Even though significant correlation is observed between the process variable and neutron flux, one cannot easily expect the feasibility of RC estimation. Strictly speaking, the RC can be estimated only when there is sufficient influence from the process variable to neutron flux in the form of open-loop system (causality condition). Hence it is important to check, through the noise analysis, the causal relation as well as the correlation. In the present noise analysis we examine this based on the signal transmission path (STP) analysis. It evaluates the causal relation between the signals with the aid of multivariate time series analysis. The result will provide information on whether or not there is sufficient correlation between the signals, if there is any feedback effect between them, which variable acts as the cause and which as the effect, and so forth.

The noise analysis has been carried out at BWRs of different type, i.e., BWR-4, -5 and ABWR, to evaluate the feasibility of the method proposed in this paper. This paper presents the method of noise analysis for the RC estimation and the result of feasibility study carried out through its application to BWR noise data.

II. Method for Estimating RC Based on Noise Analysis

1. Principle for the estimation of RC

The RC for a process variable is defined as the change in reactivity per unit change in the process variable under evaluation. It may be estimated empirically by evaluating the magnitude of reactivity response to a change in the process variable. Generally speaking, however, the reactivity cannot be measured directly except that the reactivity meter is available. An alternative way is to estimate it by evaluating the response magnitude of the neutron flux when applying disturbances to the process variable. For small perturbations around the process steady state, the RC may be described using the Laplace transform expression as follows:

\[
\alpha_X(s) = \frac{\delta \rho(s)}{\delta X(s)} = \frac{\delta N(s)/N_0}{\delta X(s)} = \frac{G_N(s)C(s)G_X(s)}{G_P(s)}
\]

where \(\alpha_X\) denotes the RC for the variable \(\delta X\), \(\delta \rho\) the reactivity, \(\delta N\) the neutron flux, and \(N_0\) the neutron flux level, respectively. The variable \(\delta X_m\) denotes the measurement of \(\delta X\). The transfer functions (TFs) in Eq.(1) are defined as follows:

- \(G_N(s) = (\delta N/N_0)/\delta X_m\); TF from \(\delta X_m\) to \(N\),
- \(G_X(s) = \delta X_m/\delta X\); TF for the process sensor system,
- \(G_P(s)\); TF for the neutron kinetics, and
- \(C(s)\); Compensation factor for \(G_N(s)\) due to measurement noise in \(\delta X_m\).

With Eq.(1) as the basis, one can estimate the RC experimentally, where \(G_P(s)\) is given theoretically, the signal level \(N_0\) and \(G_N(s)\) are determined experimentally. \(G_X(s)\) is given either experimentally or theoretically. Depending on the sensor response characteristics, it may give significant influence on the result of RC estimation. The compensation factor \(C(s)\) is necessary as explained later. It should be noted that the estimated RC in terms of Eq.(1) is a function of frequency and we call it RC function. As explained later the RC is estimated by taking the mean value of the function in an appropriate frequency band.

In the present noise analysis we analyzed signals of APRMs for the neutron flux and dome pressure, pressure difference at the core plate, core flow and the pump deck pressure difference for RIP (Reactor Internal Pump) (in the case of ABWR) as candidates for the process variable.

2. Method for RC estimation based on noise analysis

Noise analysis can be applied to empirically determine the RC. Its advantage is that one makes use of natural fluctuations in the process under evaluation as the source of reactivity disturbance. Hence it is not necessary to give any deliberate perturbations to the reactor plant.

The TF \(G_N(s)\) may be obtained by the noise analysis for the process variable as the input and neutron flux as the output. It is estimated based on either the fast Fourier transform (FFT) or a process identification technique.
As explained in Sec.1, the measurement signals are more or less contaminated by additional disturbances called measurement noise. This may bring about bias in the TF estimation. There are three relations available to estimate the TF that are described in the frequency domain as follows:

\[
\begin{align*}
G_{\text{est}}(j\omega) &= \frac{P_{XX}(j\omega)}{P_{NN}(j\omega)} \\
G_{\text{est}}(j\omega) &= \sqrt{P_{NN}(j\omega)/P_{XX}(j\omega)} \\
G_{\text{est}}(j\omega) &= \sqrt{P_{NN}(j\omega)/P_{XX}(j\omega)}
\end{align*}
\]

where \(P_{XX}(j\omega)\) is the power spectral density (PSD) of the process signal, \(P_{NN}(j\omega)\) the PSD of neutron flux and \(P_{NN}(j\omega)\) the cross-power spectral density (CPSD) between them, respectively. \(G_{\text{est}}(j\omega)\) is the gain of estimated TF. It is known that the GNX1 and GNX3 give the upper and lower limit of the TF estimate, respectively, while GNX2 is the geometrical mean of GNX1 and GNX3. The TF GNX is estimated by taking into account the measurement noise only in the input, while that of GNX3 the measurement noise only in the output. In practice, however, both the input and output may be contaminated by the measurement noise. Accordingly the estimated TF tends to get biased and the true TF should be in between them. It is often so that the difference between the two TFs is significant unless the coherence is very high between the input and output. As a method to alleviate the bias problem, it has been proposed to take the mean value of the two TFs.\(^4\)

The bias may be reduced further if one can measure multiple signals for either or both the input and output signals. The compensation factor \(C_f\) can be deduced with the aid of multiple APRMs and process signals as summarized below.\(^2\)

<table>
<thead>
<tr>
<th>Transfer Function</th>
<th>Compensation Factor ((C_f))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(G_{\text{NNX1}})</td>
<td>(\sqrt{\gamma_{NN}(\omega)/\gamma_{NX}(\omega)})</td>
</tr>
<tr>
<td>(G_{\text{NNX2}})</td>
<td>(\sqrt{\gamma_{NN}(\omega)/\gamma_{NX}(\omega)})</td>
</tr>
<tr>
<td>(G_{\text{NNX3}})</td>
<td>(\sqrt{\gamma_{NN}(\omega)})</td>
</tr>
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</table>

In Table 1, \(\gamma_{NN}(\omega)\) is the coherence between two groups of APRMs, e.g. APRM-A and APRM-B. \(\gamma_{NX}(\omega)\) is the coherence between the process variable and neutron flux. Namely, the compensation factor \(C_f\) is described by the coherence between the multiple signals and that between the input and output. The application of the compensation factor in the table gives a weight on the estimated TF according to the degree of measurement noise in both the input and output.

The actual estimate for the TF is obtained by giving an empirical weight on the experimentally determined TFs as follows:

\[
\hat{G}_{\text{est}}(\omega) = (1-\mu)G_{\text{est}}(\omega) + \mu C_f(\omega)G_{\text{est}}(\omega), \quad (0 \leq \mu \leq 1)
\]

where \(\hat{G}_{\text{est}}(\omega)\) is the final estimate of the TF and the coefficient \(\mu\) is the weighting factor.

The estimated TF is a function of frequency and hence the RC, too, when substituting it into Eq.(1). A question remains on which frequency point shall be used for estimating the RC. Several alternatives are available. In the present study we adopted the mean value of the TF over a given number of frequency points around the coherence peak within a predetermined frequency interval.

3. Procedure for the RC estimation based on noise analysis

The noise analysis for the RC estimation is carried out according to the following step:

1) Analyzing the correlation and causality: The coherence analysis is performed to check the effective frequency region with significant correlation between the process variable and neutron flux. The causality of the signal power propagation is checked based on the STP analysis, where the noise power contribution (NPC) function and coherence function are compared between the two variables. Briefly speaking, the NPC function provides the information on how much the signal power propagates from one variable to the other. This allows the identification of causal relation between the variables.

2) Determining the compensation factor: The compensation factor in Table 1 is determined based on the coherence analysis for multiple signals of APRMs and process signals. Next the mean value is taken for the multiple signals to obtain the time series data to be analyzed.

3) Estimating TF: The TF is estimated using Eq.(2) for frequencies adopted by the noise analysis in step-1). Among the three TFs, the geometrical mean \(G_{\text{NNX2}}\) after having applied the weight by Eq.(3) is adopted to estimate the RC.

4) Inserting the result to Eq. (1) to estimate the RC; The mean value is calculated to finally obtain the RC estimate by taking the frequency interval with high coherence.

Other functions such as kinetics model and sensor characteristics must be prepared separately. For the kinetics model, we adopted the parameters derived from the SIMULATE code calculation for each reactor examined in the present study. The sensor characteristic \(G_{\text{est}}(s)\) has been assumed to be a first order system with the time constant of 0.1 sec.

III. Noise Analysis for the Feasibility Study

The noise analysis has been carried out for data collected at BWRs of different type, i.e. BWR-4, BWR-5 and ABWR, respectively. Signals of APRM, dome pressure (PRS), pressure difference of the core plate (CPdP) and total core flow (CFLW) have been evaluated. In the case of ABWR, RIP deck pressure difference (PDrp) has also been included in the analysis. The latter four variables have been considered as the variable that may be used to estimate the RC.

Figure 1 shows the coherence and phase difference curves obtained by the noise analysis for each type of BWRs. There are two frequency regions where the coherence is high, i.e.
below 1Hz and about 3 to 5 Hz. For all cases, the signals of CPdP and CFLW (or PDdP in the case of ABWR) have significant correlation with APRM between 0.1 and 1Hz, while PRS in further lower frequencies. In frequencies below 1Hz the phase is positive, suggesting that APRM leads the process signals.

In frequencies around 3~5Hz, the coherence is significant for PRS. CPdP has also strong correlation in the case of BWR-4 but not CFLW or PDdP. In this frequency region the phase for PRS leads APRM. The result of coherence analysis suggests that CPdP and CFLW (PDdP in the case of ABWR) between 0.1 and 1Hz, or PRS around 3Hz may be used to estimate the RC.

Figure 2 gives the result of STP analysis for the case of BWR-4. The NPC from PRS to APRM is high and close to the coherence in frequencies around 2~5Hz, while the NPC to the opposite direction is low. This suggests the influence from the pressure to neutron flux in this frequency region. On the other hand the causal relation between CPdP and APRM is shown to be opposite, suggesting that the signal power propagates from APRM to the core inlet flow. In frequencies around 0.1~1Hz, the NPC function indicates the noise power propagation from APRM to CPdP but not to the opposite direction. The result is similar to the case of CFLW, too. As the result of noise analysis for BWR-4 data, the PRS in frequencies around 3Hz has been selected to estimate the RC.

The analysis has bee carried out also for BWR-5. The result was similar to that of BWR-4. But the correlation was considerably lower and hence it was found to be difficult to estimate the RC with satisfactory accuracy.

In the case of ABWR, PDdP was included in the analysis together with CPdP and PRS. The result in Figure 3 exhibits that different from BWR-4, PDdP and CFLW signals give influence on APRM in frequencies around 1Hz in addition to PRS at around 3~5Hz. The result of noise analysis suggests that PRS around 3~5Hz, and CPdP and PDdP around 1Hz may be used to estimate the RC.

IV. Estimation of Reactivity Coefficient (RC)

The method presented in Sec. II has been applied to BWR-4 data to estimate the RC. Figure 4 shows an example of the RC curve obtained for PRS, in which the weighting factor of 0.5 was applied to reduce the bias in the estimated RC. This provides the estimate of pressure coefficient. As examined in Fig.1, significant perturbation is expected from the pressure to neutron flux at about 2~5Hz. The RC was estimated from the mean value of the RC curve in a given interval around the coherence top.

Noise analysis was performed for data recorded at ten different burn-up points in the same reactor cycle. Figure 5 plots the estimated RC values as a function of burn-up. Three curves by the noise analysis are upper limit, geometrical mean and lower limit, respectively. In the present noise analysis the geometrical mean curve is adopted as the RC estimate. The RC values indicate slowly increasing tendency as the burn-up.

In order to examine the RC estimates by the noise analysis, the result was compared with that by a core analysis code. The void coefficient was estimated by the static reactivity evaluation using the BWR core analysis code TARC/BF1-ENTREE.50 for each burn-up point when the noise measurement was conducted. Figure 6 shows the comparison of the two results in terms of relative value. As the long-term trend, both results agree well, increasing slowly towards the end of cycle. Through the core state evaluation, it was observed that at the beginning of cycle the coolant flow had been kept high by means of control rod adjustment and then it had been reduced towards the end of cycle. It is conjectured that high coolant flow at the beginning of cycle led to high coolant density and hence low void fraction, which in effect yielded a tendency of low sensitivity of the reactivity to the void fraction change, or in other words, the low value of void coefficient. As the burn-up increased, the core flow decreased, which increased the average void fraction in the core. This tended to increase the void coefficient.

The correlation between the two results, as given in Fig.7, was found to be 0.77. This suggests that as the trend of RC behavior, the RC estimated by the noise analysis for pressure to neutron flux follows well the void RC behavior.

A similar analysis has been carried out for data collected at the ABWR. The RC was estimated by the noise analysis of CPdP and APRM. Since the coherence is high, as shown in Fig.1, in frequencies around 0.1 to 2Hz, the RC curve in this region was used to estimate the RC. The BWR core dynamics in this frequency region include feedback effects due to nuclear-thermal-hydraulics couplings. The noise analysis should yield the TF from the core flow to neutron flux including the feedback loop. Hence it is expected that the estimated RC be correlated with the reactor stability. Figure 8 is the plot of the estimated RC vs. decay ratio (DR) for each of noise measurements. The DR is very low ranging almost zero to 0.16. Generally the DR estimates tend to scatter for a stable core with very low DR. Nevertheless the correlation was found to be 0.78 between them, being high and indicating increasing tendency in the RC in proportion to the DR.

V. Examination of Results and Discussion

1. Examination of the Validity of Estimated RC

The method for RC estimation presented in this paper is based on the noise analysis between a process variable and neutron flux. Those variables like pressure and core flow primarily affect the reactivity via average void fraction change in the core. The mechanism of how the process variable gives influence on the neutron flux could be different at different frequency regions.

In very high frequencies above ~20Hz, i.e. the cut-off frequency in the reactor kinetics determined by the ratio of $\beta/\lambda$, i.e. the ratio of delayed-neutron fraction and neutron generation time, one cannot expect effective information to estimate the RC.

In frequencies below it and above ~1Hz, the dynamics
from the process variable to the neutron flux can be viewed as an open-loop system.

In frequencies between 0.1 and 1Hz, it is expected that the feedback effect may become apparent between the neutron flux and the core void. This is observed as a resonant peak in the power spectrum of neutron flux. Under the condition with feedback effect, the RC estimate, if we use the estimated TF, may get biased depending on the relation of the process variable and the feedback. If one can directly measure the variation of averaged void fraction over the core, then it is, in principle, possible to estimate the TF from the void to neutron flux regardless of void feedback. In this case one can cut the feedback path to estimate the TF in the loop. Accordingly the void RC can be estimated by the noise analysis. However this is in practice unfeasible. On the other hand, if the process noise, for example, the core inlet flow noise, actively gives influence on the core dynamics, then what one can estimate by the noise analysis should be the closed-loop transfer function in which the void reactivity feedback is included as the internal feedback. This could eventually hinder the direct estimation of RC by the noise analysis, requiring its compensation by one way or another.

For further lower frequencies, it becomes difficult to estimate the RC by the noise analysis, since the feedback effects due to fuel temperature and process control loops should also affect the estimation of TF.

In the present noise analysis, we used the information of noise propagation from the process variable to neutron flux in frequencies around 2–5Hz. The dynamics relation in this region can be viewed as that of an open-loop system. Therefore if there is strong noise propagation, it should be possible to estimate the RC.

In the previous section we compared the estimated pressure RC by the noise analysis with the void RC obtained by the code prediction. This is considered to be valid if the following relation holds in the whole operation cycle, i.e.

$$\alpha_P = \frac{\delta P}{\delta P} = \frac{\delta V}{\delta V} = \beta = \alpha_{\nu} |G_{VP}|$$ (4)

where $\alpha_P$ is the pressure RC, $\alpha_{\nu}$ the void RC and $|G_{VP}|$ the gain of the TF from pressure to average void fraction, respectively. If the TF $|G_{VP}|$ does not change at about the rated power over one cycle, what one observes in the pressure RC behavior should be in proportion to the void RC. As observed in Fig.6, the relative value of the pressure RC exhibited good agreement with that of void RC obtained by the code prediction and hence the assumption of Eq.(4) appears to hold fairly well. This gives us a confidence on the present noise analysis approach.

2. Discussion of Noise Source

The feasibility of the RC estimation by noise analysis depends on the noise source. The RC estimation is possible only when there is sufficient noise excitation from the process variable to neutron flux. Unfortunately, however, not so much has been made clear about the noise source in a BWR from the viewpoint of RC estimation.

It appears that the noise excitation in the pressure and coolant flow at the core bottom is due to standing wave in the pressure. This has been applied in a PWR to estimate the pressure RC. This oscillation has been observed clearly in BWR-4 and also in ABWR but not so clearly in BWR-5. But it is expected that the pressure oscillations of this kind exist in BWR-5, too and the improvement of noise measurement technique could enhance the correlation.

In frequencies between 0.1 and 1Hz, a good correlation was observed between CPdP and APRM and also between CFLW (PDdP in the case of ABWR) and APRM in all the three BWR types. However, the result of STP analysis suggested different noise sources depending on the reactor type.

In BWR-4 and −5, the result of STP analysis suggests that noise propagation is from APRM to process variable. On the contrary, in the case of ABWR, an external noise was suggested to exist outside the core, which affects the core inlet flow and further the neutron flux.

It appears that these different noise sources depend upon the coolant flow driving system in the recirculation loop. Namely in the case of ABWR, the RIs are in the recirculation loop, which actively drive the coolant flow to the core. The coolant flow fluctuations induced by the RIs is interpreted as the driving source to the core flow variation, which in its turn gives influence on the power fluctuation.

In the case of BWR-4 and −5, the result of noise analysis suggested the noise source in the core, which affects the core inlet flow. One possible interpretation of the noise source in these BWRs is the void noise in the core. Namely, the core void fluctuations give influence on both the neutron flux and coolant inlet flow. The former forms void reactivity feedback and the latter the thermal-hydraulic feedback, which in its turn induces the coolant inlet flow fluctuations observed by the CPdP. The void fluctuations are observed by APRM without delay, while the latter by CPdP with a certain delay due to thermal-hydraulic dynamics. This means that the noise source to the CPdP and CFLW signals in BWR-4 and −5 is the void noise in the core.

Yet another interpretation is that the result of noise analysis is influenced by the sensor characteristics and the causal relation must be re-examined by taking the sensor dynamics into account. This is true especially when the sensor for the input signal has a characteristic with large time constant compared with that for the output. In such a case the causal relation may become reversed in appearance. This can happen for the signal pair of core inlet flow and neutron flux, since the pressure-difference sensor has a certain delay in the response compared with the APRM.

In Sec. IV, the result of noise analysis for the ABWR was presented as the RC estimate for the coolant flow. Based on the above interpretation, however, the estimated TF should be the closed-loop one from the coolant flow to neutron flux including the void feedback. In order to accurately estimate the RC, the influence of the feedback effect should be taken into account.
VI. Concluding Remarks

The paper presented the method for RC estimation based on the noise analysis. The method has been applied to noise data collected at BWRs of three different types, i.e. BWR-4, -5 and ABWR. The process variables such as neutron flux, dome pressure, coolant flow, pressure-difference of the core plate, RIP pressure-difference have been examined to evaluate the feasibility of the RC estimation.

The result suggested that in the case of BWR-4 and ABWR the pressure signal in frequencies around 2~5Hz could be used to estimate the pressure RC. The estimated RC for the BWR-4 was compared with the void RC obtained by the core analysis code. The results exhibited good agreement in terms of relative RC. This demonstrates the potential of the present method for the RC estimation.

The noise analysis for the ABWR data also indicated the possibility of RC estimation using the CPdP signal for frequencies around 1Hz as well as that using PRS signal around 3~5Hz. The estimated RC for CPdP has been shown to have good correlation with the DR of the neutron flux signal. Namely the current result carries information on the reactor stability. This may be quite natural since the estimated TF from the core inlet flow to neutron flux includes the void reactivity feedback loop. In this respect, for the accurate estimation of RC, the current result must be corrected for by taking into the feedback effect.

The feasibility of the RC estimation is intimately related to the noise source and its propagation mechanism. However they are not so clearly understood in BWRs. The noise generation and propagation mechanism could be different among different type of BWRs. Even in the same type of BWRs, they could be different quantitatively from one reactor to another. More accurate knowledge on these will contribute to the further accurate measurement of RC.

Current state of the art for the method of RC estimation is that it can be used to estimate the pressure RC in the sense of relative value. It may be compared with the void RC, too, to track the long-term behavior. Concerning the absolute value of the RC, there remains a lot to be done. It requires the accurate information on the sensor system to recover the actual process signal behavior in frequencies of concern. For estimating the void RC, the pressure-to-void TF must be included to convert the estimated value.

The signal processing method and its implementing procedure has been developed in a general form for estimating the RC in a BWR. It requires only reactor kinetics parameters and minor parameter tunings, for example, to select appropriate frequency interval. It can be applied to the on-line monitoring of RC in an operating BWR.

VII. Acknowledgment

The present authors are indebted to Dr. A. Hotta in TEPCO SYSTEMS for his contribution to the present work by providing the void RC values estimated by the core analysis code, TARC/BF1-ENTRÉE, together with the kinetics parameters used in the present study.

VIII. References

Fig. 1 Result of coherence analysis for three different BWR types, where the upper figure shows the coherence and the lower the phase difference curves, respectively, between the process signal and APRM.

Fig. 2 Result of STP analysis between dome pressure (PRS) and APRM (left), and core plate dP (CPdP) and APRM (right) for data from BWR-4, indicating significant perturbations from PRS to APRM, and that from APRM to CPdP in frequencies from 2 to 5Hz.
Fig. 3 Result of STP analysis between PRS and APRM (left), between CPdP and APRM (center) and between PDdP and APRM (right), respectively, for data from ABWR, indicating significant perturbations from PRS to APRM for 3–5 Hz, and that from CPdP and PDdP to APRM in frequencies around 1 Hz.

Fig. 4 The RC curve for signals of PRS and APRM obtained by the noise analysis for data from BWR-4.

Fig. 5 Estimated RC for the pressure at a BWR-4, indicating slowly increasing tendency as the burn-up.
Fig. 6 Comparison of estimated RCs in terms of relative value; pressure coefficient by the noise analysis (thick real line) and void coefficient by the code prediction (thick dotted line) for a BWR-4.

Fig. 7 Correlation between the pressure coefficient estimated by noise analysis and void coefficient by code prediction, exhibiting high correlation with the correlation coefficient of ~0.77.

Fig. 8 Plot of estimated reactivity coefficient for core plate pressure difference vs. decay ratio (DR) at an ABWR.