The evaluation of a group motion for FBR core subassemblies under the seismic condition over Design Basis Earthquake Ground Motion

Masahiko ARIYOSHI, Akira YAMAGUCHI and Takashi TAKATA
Osaka University
2-1 Yamada-Osaka, Suita, Osaka 565-0871, Japan
ariyoshi_m@qe.see.eng.osaka-u.ac.jp, yamaguchi@see.eng.osaka-u.ac.jp
takata_t@see.eng.osaka-u.ac.jp

Hiroshi ENDO
Central Research Institute of Electric Power Industry
2-11-1 Iwadokita, Komae-shi, Tokyo 201-8511, Japan
h-endo@criepi.denken.or.jp

ABSTRACT

The seismic Probabilistic Risk Assessment (PRA) for Fast Breeder Reactors (FBRs) has been carried out to confirm that the seismic safety is equivalent to that of Light Water Reactors (LWRs). The seismic response on the reactor structure of FBRs causes seismic reactivity. The group motion of fuel assemblies is one of typical seismic response. So that much attention has been paid on the reactivity insertion mechanism due to the group motion of fuel assemblies and it's consequence during the earthquake over the Design Basis Ground Motion (DBGM) condition. When the displacement of each subassembly is moving toward the same direction, each gap reduces coherently and the radial core compaction occurs, which results in positive reactivity insertion. We evaluate the gap reduction characteristics at the mid-plane of core by using a correlation coefficient. As a result, the fuel subassemblies are most concentrated when the input seismic motion of about 5Hz frequency and 40m/s^2 acceleration is applied. The amount of reactivity insertion is estimated approximately 1$ that corresponds to prompt criticality.

KEYWORDS

FBR, transient overpower, subassemblies group motion, core disruptive accident,
Design Basis Ground Motion

1. INTRODUCTION

Fast Breeder Reactor (FBR) plants are consisted with system components, which are designed by the concept of thin wall structure because of the high temperature sodium coolant. The response displacements of an earthquake tend to be large in comparison with Light Water Reactors which structures are designed to withstand high pressure load. Therefore, the structural evaluation for the Design Basis earthquake Ground Motion (DBGM) is important. If seismic stress exceeds a limit of the structural strength under beyond DBGM condition, a sodium leak and the loss of the core coolable geometry may occurs and causes the core disruptive accident (CDA). Then, for the earthquake greater than the DBGM condition, a systematic evaluation by probabilistic Risk Assessment (PRA) is necessary.

The conventional seismic PRA has been focused on mostly structural failures, and Transient

Over Power (TOP) event has not been investigated extensively. However, the reactivity insertions induced by the seismic motion of control rods and fuel subassemblies during earthquake condition may cause excess reactivity insertion. The group motion of subassemblies, one of the typical seismic response in FBRs, is a phenomenon of almost all subassemblies move and collide simultaneously because the gaps between neighboring subassemblies are narrow. When each gap reduces coherently and the core compaction in lateral direction occurs, the positive reactivity insertion is introduced. The study of the seismic induced TOP has been conducted by one of the coauthors for vertical displacements of control rods [1]. The reactivity insertion by the group motion of fuel subassemblies in lateral direction has been evaluated only under DBGM condition [2].

Therefore, much attention has been paid to core damage scenarios and phenomena which are caused by reactivity insertion due to the fuel subassemblies group motion under beyond DBGM condition. The purpose of this paper is to clarify the mechanism of the reactivity insertion by fuel subassemblies group motion, and preventing condition from development to the CDA.

2. THE POSSIBILITY OF THE CDA CAUSED BY THE FUEL SUBASSEMBLIES GROUP MOTION

The amount of the reactivity insertion about the typical compaction mode of fuel subassemblies was evaluated by Japan Nuclear Energy Safety Organization (JNES) [3]. A middle sized FBR core, approximately 700MWt, was assumed. The reactivity insertion was evaluated statically upon the effective neutron multiplication factor which is calculated by multi-groups Monte Carlo transportation calculation code GMVP. The results were 1.6$ in "the compaction mode toward the core center", and 0.7-0.9$ in "the total deflection mode in one lateral direction". This positive reactivity effect is enhanced in the Outer Core (OC) region where the neutron flux distribution is inclined. So the reactivity insertion as a function of OC region area is shown in Fig.1

The characteristic of the CDA caused by the seismic reactivity insertion was investigated by JNES [3]. The seismic induced reactivity insertion was assumed to be a sine wave, and the parameters are the frequency (2 - 10Hz) and amplitude (1 - 5$ reactivity). In the case of reactivity amplitude 2$, the reactivity insertion reaches the fuel melting condition at the first wave. In the case of reactivity amplitude 1.15$ and frequency 5Hz, core melt zone expands in a few seconds after the beginning of the reactivity insertion, finally the reactivity exceeds prompt criticality by the molten pool sloshing.

It is thought that a criterion to prevent the CDA is approximately 1.15$ at the frequency 5Hz. On the other hand, the reactivity insertion is approximately 1.6$ at "the compaction mode toward the core center", so that the possibility of CDA cannot be denied. This compaction mode, being assumed that each gap between neighboring subassemblies at spacer pad close completely at same time with all subassemblies on whole core region, are considered not realistic. However, the gap between neighboring subassemblies at mid-plane is reduced more than that at the spacer pad, because of the bow-shaped deformation when subassemblies are colliding. So if the core compaction area is sufficiently large, the reactivity insertion may exceed a criterion to prevent the CDA.

Therefore, in this article, we focus on the mechanism of the subassemblies group motion and clarify the magnitude of the subassemblies compaction that causes positive reactivity insertion.

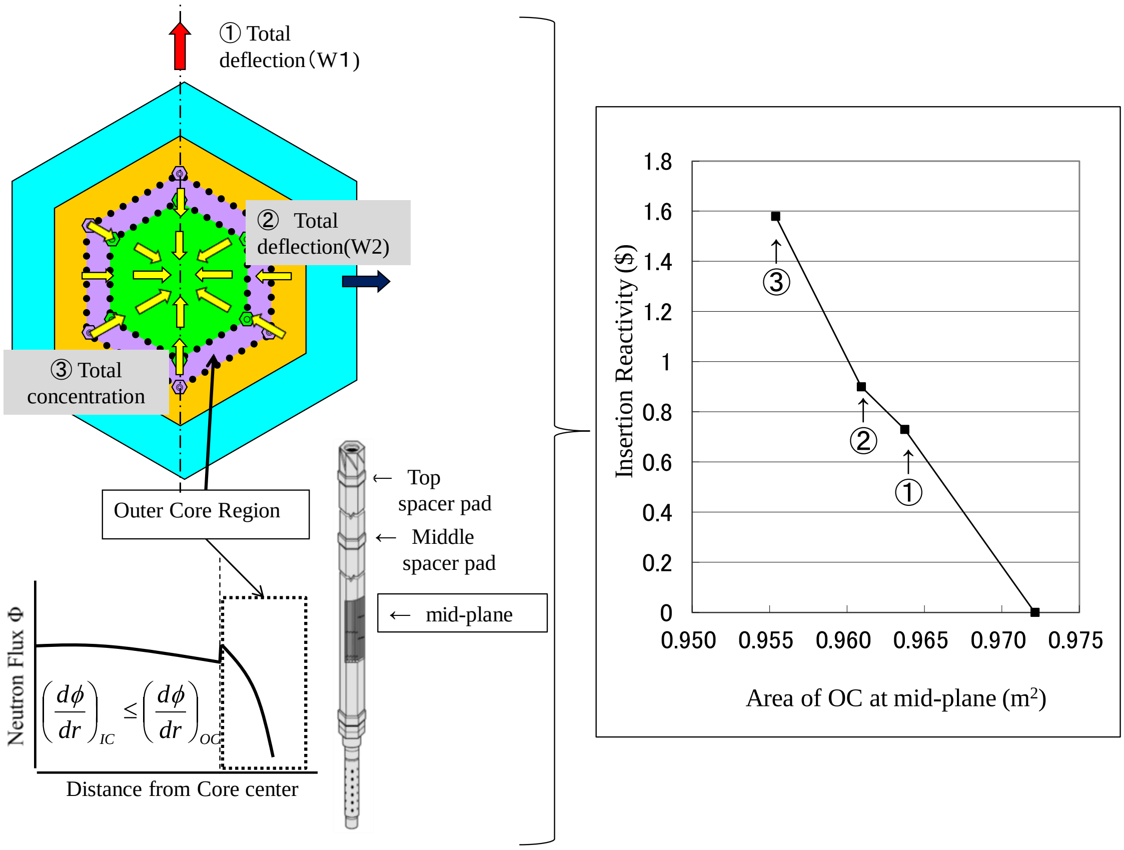


Fig.1 Insertion reactivity of typical fuel concentration mode

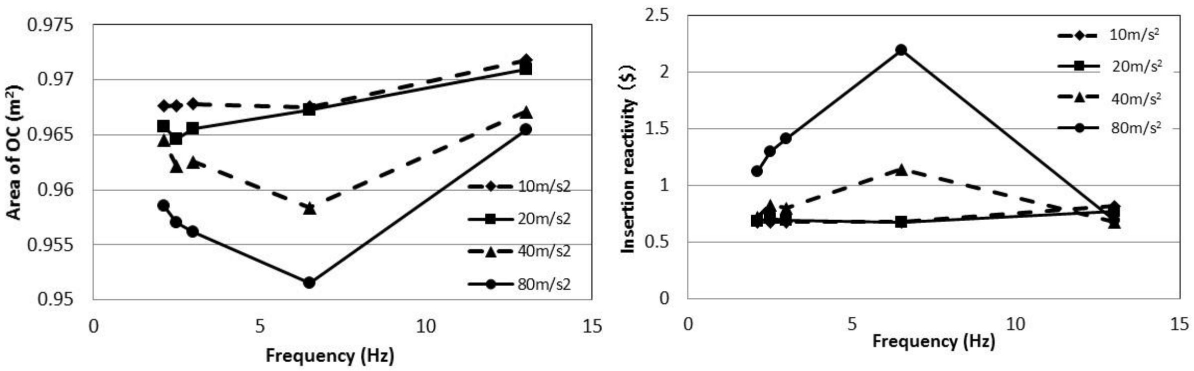
3. THE ANALYSIS OF THE SUBASSEMBLIES GROUP MOTION

We carried out subassemblies group motion analysis using structural analysis code ABAQUS to clarify the possibility that "the total deflection" mode and "the compaction to the core center" mode occurred by earthquake.

The middle-size 700MWt FBR core is assumed. Approximately 700 subassemblies are contained inside the core barrel, and those are considered in the analysis model. The fuel subassembly is modelled by a beam element, and collision rigidity is considered at spacer pad. The subassembly is supported by the core support plate by contacting at the spherical seat with rotation free, so this part is modeled by pin connection element. The rotation is restricted by contacting of entrance nozzle to inner surface of connecting tubule. The influence of the fluid in the subassembly motion is considered on both of the fluid force and reduction of the natural frequency based on the Fritz theory [4][5][6][7].

A sine wave is applied to evaluate the characteristic of the subassemblies group motion with regard to both of the exciting acceleration and frequency. Exciting direction is W1 as shown in Fig.1. As a result, the OC region area becomes smaller as the acceleration increased as shown in Fig.2. Furthermore, OC region area becomes minimum at exciting frequency of 6.5Hz under conditions of 40m/s^2. Therefore the OC area is dependent on not only the acceleration but the frequency.

In this case, subassemblies were more centralized than "the total deflection" evaluated in the W1 direction excitation case, and it is predicted that the reactivity insertion exceeds 1$ according to the relation of the OC region Area and the amount of reactivity as shown in Fig.1 and 2.



(a) Area of OC (b) Reactivity

Fig.2 Analytic results of group motion of subassemblies

4. THE CONSIDERATION OF THE MECHANISM OF THE SUBASSEMBLIES GROUP MOTION

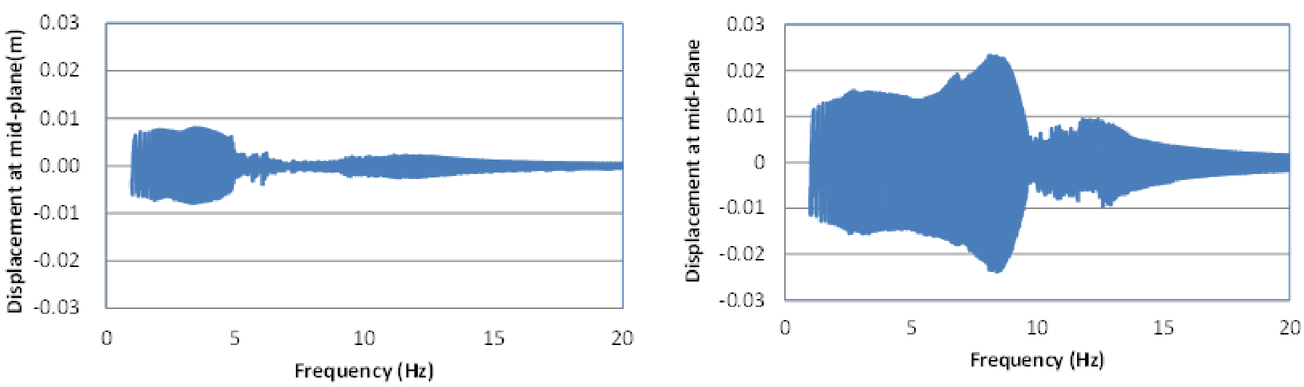
4.1. The transition of vibration mode caused by collision behavior

To clarify the mechanism of the subassemblies compaction which is more than "the total deflection" condition, the relation of the vibration mode and collision behavior is confirmed.
Before the collision of subassemblies the cantilever mode vibration (eigenvalue; 1.7Hz) is excited. On this mode, maximum displacement is excited at the top of subassembly, and the gap between neighboring subassemblies is minimum at the top spacer pad. So a collision of the subassemblies occurs at the top spacer pad position. After the collision, the vibration mode of the subassembly changes to upper and lower supported mode (eigenvalue; about 8.9Hz). On this mode, the displacement becomes large at the mid-plane of the core where the reactivity worth is maximum. The displacement of the subassembly depends on the vibration mode, so a series of analyses is carried out to investigate the dependence of the vibration mode on the exciting frequency and acceleration. The analysis object is the single lined group of subassemblies crossing the core center from the bottom to top in Fig. 1. The single-lined assemblies are excited in in-line direction (W1 direction). The exciting acceleration is expressed as the Eq. (1) with two different amplitudes, A_o is 10m/s^2 and 40m/s^2. The frequency is swept and is given a function of time as shown in Eq. (1).

$$A = A_0 \sin\left\{2\pi\left(21 - \frac{t}{8}\right)t\right\} \tag{1}$$

A : Exciting acceleration at analysis time t (m/s^2)
A_0 : Maximum acceleration (m/s^2)
t : Analysis time（s）

Fig.3 shows displacement at the mid-plane of a fuel subassembly loaded near the core center. In the case of exciting acceleration 10m/s^2 (Fig. 3(a)), the displacement becomes larger in the exciting frequency range below approximately 5Hz. The natural frequency of the cantilever mode is 1.7Hz that is included in this range. Collision at the top of the subassemblies occurs in this region because the displacement is greater than the gap. On the other hand, the range of frequency where the collision occurs expands to about 9Hz in the case of 40m/s^2 (Fig. 3(b)). This frequency is close to the natural frequency of the vibration mode of upper and lower end support. So the displacement at the mid-plane increases remarkably because of the excitation by the vibration modes. When the exciting frequency exceeds 10Hz, the top displacement becomes smaller than other region, and a collision does not occur to get closer to second of cantilever mode (eigenvalue; 11.8Hz).



(a) Exciting acceleration 10m/s^2 (b) Exciting acceleration 40m/s^2

Fig.3 Analytical result of displacement at mid-plane

4.2. The consideration of subassemblies compaction mechanism by correlation coefficient about subassemblies gap distance

We paid attention to the center distance between adjacent subassemblies $P_n(t)$ at the mid-plane to evaluate the extent of the subassemblies compaction. $\Delta P_n(t)$ is defined by Eq. (2) using the center distance as the change of the center distance from the initial condition. Therefore, $\Delta P_n(t)$ is zero at the initial condition. When subassemblies concentrate, $\Delta P_n(t)$ becomes negative value. The absolute value became larger as the increase of the compaction.

$$\Delta P_n(t) = P_n(t) - P_o = x(t) - y(t) \qquad (2)$$

$x(t)$: Displacement of subassembly n at mid-plane at analysis time t
$y(t)$: Displacement of subassembly n+1 at mid-plane at analysis time t
$P_n(t)$: Center distance between the subassemblies n and n+1 at mid-plane at analysis time t
P_0 : Center distance between the subassemblies n and n+1 at mid-plane at initial condition

Since the system is excited by a sine wave, $\Delta P_n(t)$ changes periodically. A phase of $\Delta P_n(t)$ is different and depending on a loading position of the subassembly as shown in Fig.4. So the phase difference is evaluated by using the correlation coefficient r as shown Eq. (3).

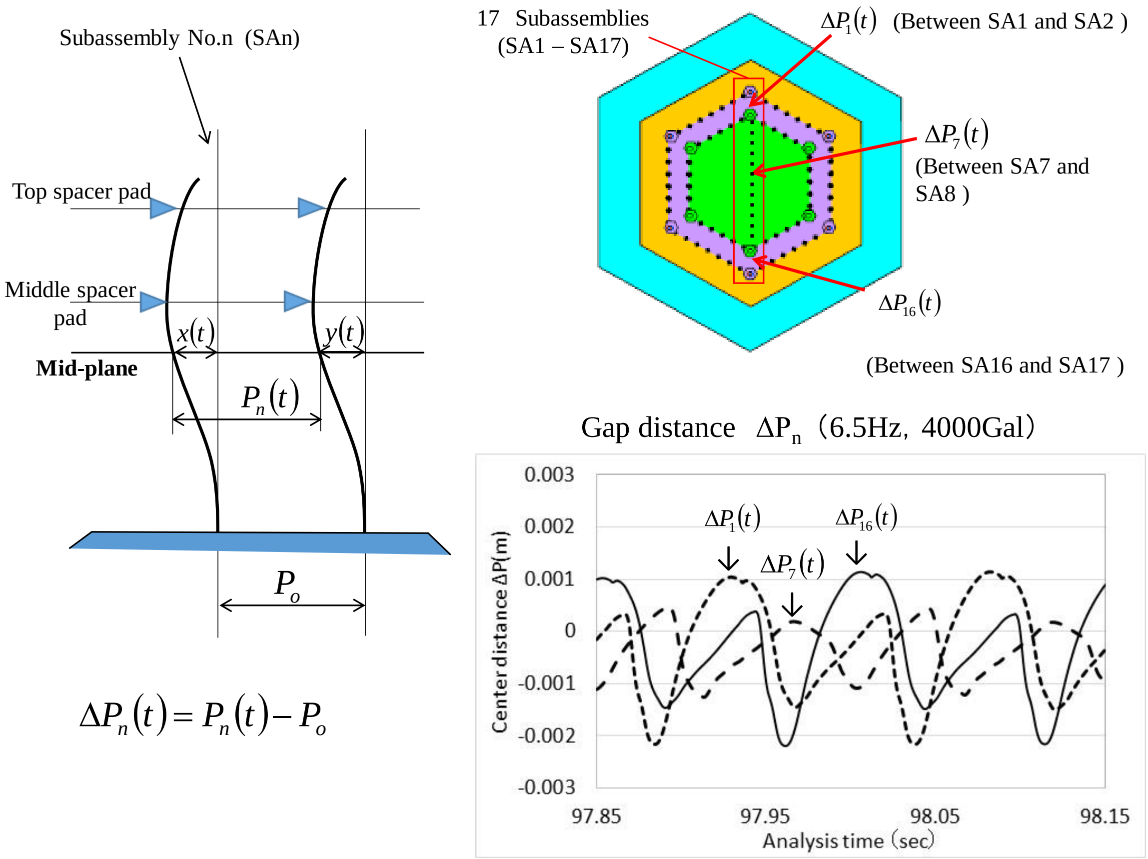


Fig.4 Phase difference of gap distances

$\Delta P(t)_1$, the change of the center difference between SA1 and SA2 shown in Fig.4, is selected as standard. And each center difference $\Delta P_n(t)$, $\Delta P_1(t)$ - $\Delta P_{16}(t)$, on the single lined 17 subassemblies shown in Fig.4 is compared with $\Delta P(t)_1$ one after another.

$$
\begin{aligned}
r &= \frac{s_{1n}}{s_1 s_n} \\
s_{1n} &= \frac{1}{m-1}\sum_{i=0}^{m}\left(\Delta P_1(t_0+i\Delta t)-\overline{\Delta P_1}\right)\left(\Delta P_n(t_0+i\Delta t)-\overline{\Delta P_n}\right) \\
s_1 &= \sqrt{\frac{1}{m-1}\sum_{i=0}^{m}\left(\Delta P_1(t_0+i\Delta t)-\overline{\Delta P_1}\right)^2} \\
s_n &= \sqrt{\frac{1}{m-1}\sum_{i=0}^{m}\left(\Delta P_n(t_o+i\Delta t)-\overline{\Delta P_n}\right)^2} \\
\overline{\Delta P_1} &= \frac{1}{m}\sum_{i=0}^{m}\Delta P_1(t_o+i\Delta t) \\
\overline{\Delta P_n} &= \frac{1}{m}\sum_{i=0}^{m}\Delta P_n(t_0+i\Delta t)
\end{aligned}
\qquad (3)
$$

t_o : The analysis time at the beginning of comparison of the center difference
Δt : Analysis time step

The change of the correlation coefficient that come with the change of exciting frequency is confirmed under the exciting acceleration 40m/s^2

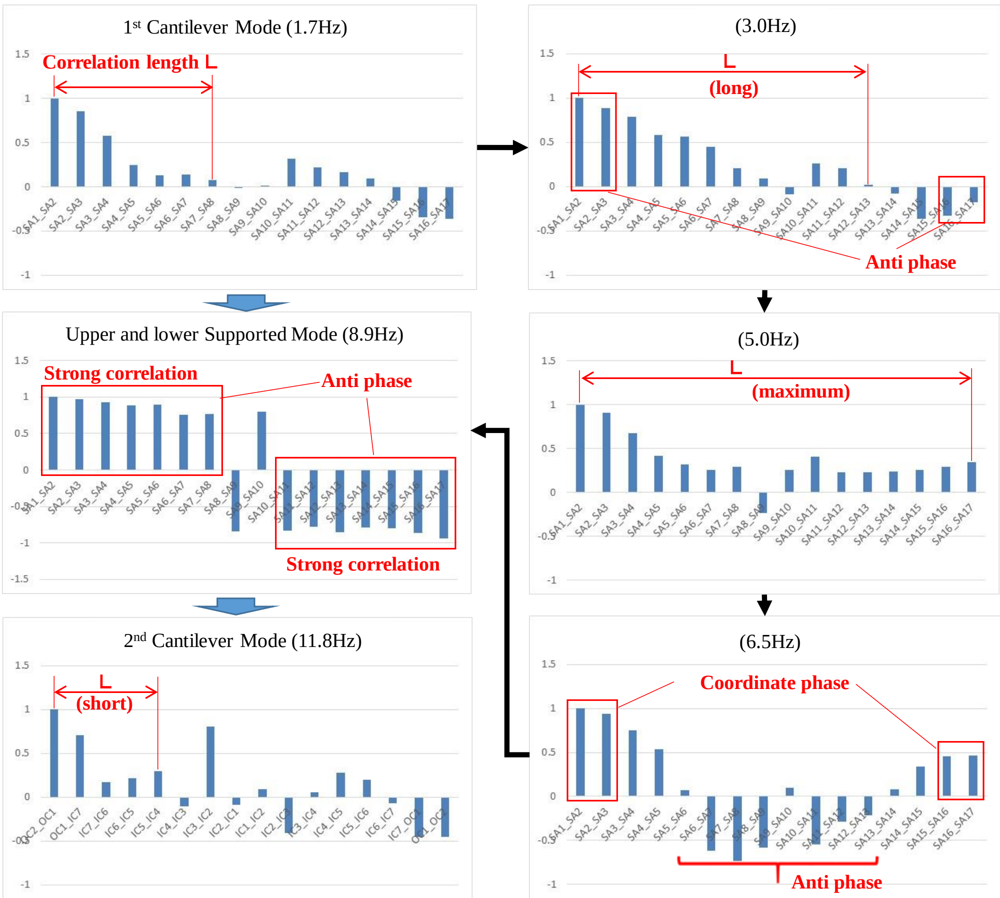
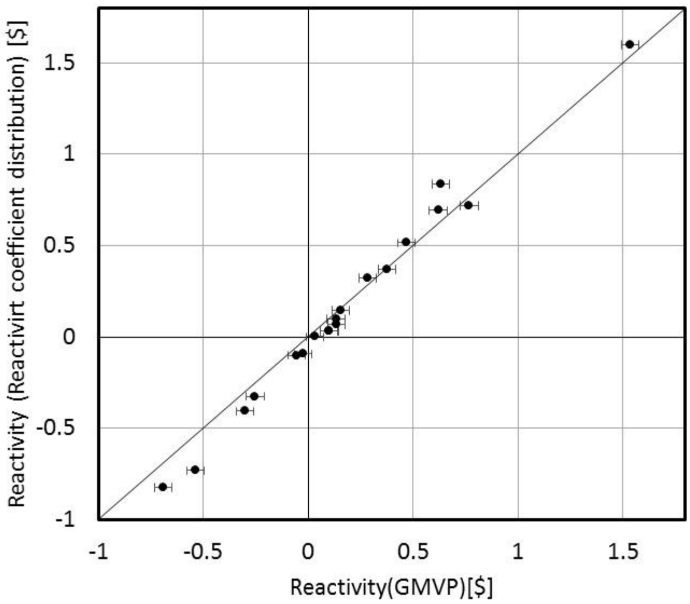


Fig.5 Correlation coefficient of gap distances

The correlation coefficient of each subassemblies is shown in Fig.5. At 1.7Hz that is the natural frequency of the primary cantilever mode, the correlative length becomes near half of the core region. Correlation becomes strong at 8.9Hz that is natural frequency of the upper and lower supported mode, but a phase is reverse with half of the core region. The correlation almost disappears at 11.8Hz that is the second natural frequency of the cantilever mode. As exciting frequency moves to the high frequency side from 1.7Hz, the correlation length gets longer, and the correlation length is maximum at about 5Hz, the region that reverses a plus and minus appears when exciting frequency increase furthermore, and a plus and minus reaches the state to turn over with half of the core region like 8.9Hz. Therefore, it is suggested that the fuel subassemblies are most concentrated at about 5Hz in the case of 40m/s^2 because all gap distances are reduced at the same time.

5. THE EVALUATION OF REACTIVITY INSERTION BY SUBASSEMBLIES GROUP MOTION

A reactivity insertion is evaluated from the amount of displacement of the subassemblies, taking account of every element of the core, i.e. fuel material, steel, and sodium. Here, the sodium reactivity consists of sodium discharge (positive reactivity) and inflow (negative reactivity) caused by the change of the gap distance. The reactivity due to subassemblies group motion is evaluated based on the perturbation method using axial distribution of the core material reactivity coefficient for each fuel subassembly [8]. The reactivity is also evaluated by multi-groups Monte Carlo transportation calculation code GMVP to confirm validity of this technique. On this benchmark calculation, it is assumed that subassemblies are moved 4mm toward the core center and the opposite direction as shown Fig.6.



Layer No.	Movement* (mm)
1	4
2	4
3	4
4	4
5	4,-4
6	4,-4
7	4,-4
8	4,-4
6,8	4
7,8	4,-4
6,7,8	4,-4
The total deflection	
The compaction to the core center	

*Positive value: toward the core center
Negative value : opposite to the core center

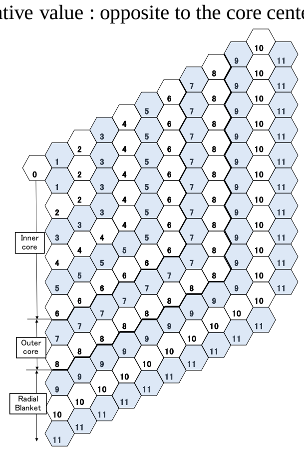


Fig.6 Verification of reactivity insertion evaluation method

Fig.6 shows the comparison of the reactivity insertion between the two methods. It is seen from the figure that the calculation results are in good agreement. The proposed approach to evaluate the reactivity insertion using the subassemblies displacement and the perturbation method is applicable and accurate enough. The subassemblies group motion has a dependency on the exciting acceleration and frequency. So the frequency sweep analysis (0.25Hz/s) using the sine wave with the acceleration amplitude of 40m/s^2 to evaluate the reactivity insertion. As a result, the maximum reactivity is inserted under the condition of approximately 5Hz frequency. The reactivity is estimated approximately 1$ as shown in Fig.7.

It is seen that the reactivity insertion decreases as the frequency goes beyond 5Hz, it is thought that the criterion to prevent the core damage, that is regarded as the reactivity amplitude 1.15 $ as discussed in section 2, is satisfied. Therefore, it is concluded that the reactivity insertion due to subassemblies group motion is close to the criterion at the exciting acceleration of 40m/s^2 and the frequency of approximately 5Hz.

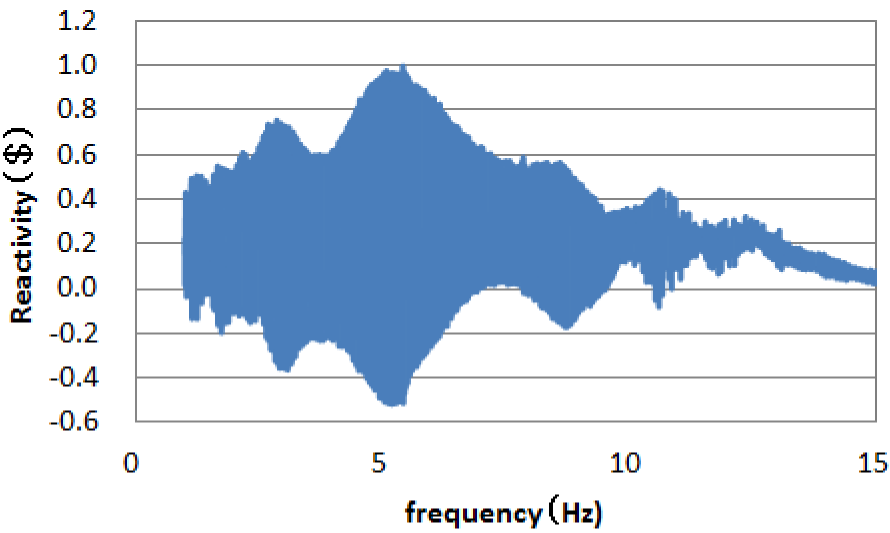


Fig.7 Analytic result of reactivity insertion (40m/s^2)

6. CONCLUSIONS

The purpose of this study is to clarify reactivity insertion mechanism due to the subassemblies group motion, one of the typical earthquake behaviors of FBRs, and to clarify the CDA limit. Therefore, in this paper, the compaction mechanism of the subassemblies is clarified, and the reactivity insertion is compared with the CDA prevention criterion.

Outline of the result are summarized as follows:

(1) Cantilever mode (eigenvalue; 1.7Hz) that only a lower end was supported is excited as for the vibration mode of the fuel subassembly. Because maximum displacement is excited at the top of subassembly and the minimum gap distance with neighboring subassemblies is at a top spacer pad position, a collision occurs on the top of subassemblies when exciting acceleration is large.

(2) Upper and lower supported mode (eigenvalue; about 8.9Hz) is excited as for the vibration mode of the subassembly when a collision occurs on the top spacer pad. The displacement becomes large at mid-plane where the reactivity worth become maximum.

(3) In the case of exciting acceleration 10m/s^2, the collision at the top of subassembly occurs in the exciting frequency range below approximately 5Hz. If the exciting

acceleration is 40m/s^2, the collision range expands to approximately 9Hz. The displacement at the mid-plane increases remarkably because the natural frequency of upper and lower supported mode (8.9Hz) is close to the excited frequency range.

(4) The fuel subassemblies are most concentrated at about 5Hz in the case of 40m/s^2 because all gap distances are reduced coherently. The amount of reactivity insertion is estimated approximately 1$, which is still below the CDA prevention criterion (1.15$).

ACKNOWLEDGMENTS

The authors would like to express acknowledge to Dr. T. Ishizu of JNES, Mr. H. Suzuki, Dr. R. Imai, Mr. S. Uno of Mizuho Information & research Institute Inc.

REFERENCES

1. A.TACHIBANA, M.SUZUKI, H.ENDO, "Sensitivity Analysis on Safety Limits of Large FBR Cores for Seismic Vertical Vibration of Control Rods", Journal of NUCLEAR SCIENCE and TECHNOLOGY, 29[1], pp. 24-49 (January 1992).
2. The seismic safety evaluation for MONJU in accordance with the revised Seismic Guide, JAEA, February 9, 2000 [in Japanese]. (http://www.nsr.go.jp/archive/nsc/senmon/shidai/taishin_godo_WG2/taishin_godo_WG2_51/siryo4.pdf)
3. T.ISHIZU, H.ENDO, M.ARIYOSHI, M.INOUE, T.NAKAJIMA, "STUDY OF CORE BEHAVIOR DURING TRANSIENT OVERPOWER (TOP) CAUSED BY SEISMIC CONDITION ON FAST BREEDER REACTOR", Proc. NTHAS8, Beppu, Japan, December 9-12, 2012, Paper Number N8P1023.
4. M.MORISHITA, SEISMIC RESPONSE ANALYSIS OF PEC REACTOR CORE MOCK-UP, PNC TN9410 93-217, Japan, Atomic Energy Agency, (1993).
5. M.MORISHITA, SEISMIC RESPONSE ANALYSIS OF PEC REACTOR CORE MOCK-UP Volume 1; Analysis of In-air Experiment, PNC TN9410 94-256, Japan Atomic Energy Agency, (1994).
6. M.MORISHITA, SEISMIC RESPONSE ANALYSIS OF PEC REACTOR CORE MOCK-UP Volume 2; Analysis of In-water Experiment, PNC TN9410 95-075, Japan Atomic Energy Agency, (1995).
7. M.MORISHITA, Development of Seismic Analysis Method for an LMFBR Core Part 4 Verification of Large Free-standing cores under Seismic Isolation Conditions, PNC ZN9410 92-014, Japan Atomic Energy Agency, (1992).
8. STUDY OF ENERGY GENERATION OF FBR ULOF EVENT BY USING SAS4A CODE, JNES/SAE08-030, 2008 [in Japanese]