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Modified Borresen's Coarse-Mesh Method for Improved Power Distribution Monitoring System Program Development for PWR

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개선된 노심출력분포 감시 프로그램 개발을 위한 수정형 Borresen 모형

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Abstract

This paper examines the applicability of the modified Borresen's coarse-mesh method(MBSN) to the core power distribution monitoring program development for the Yonggwang nuclear power plant unit 3(YGN 3) which uses fixed incore detectors for monitoring core power distribution. In so doing the modified Borresen's coarse-mesh equations are solved with core internal boundary conditions provided by the fixed incore detectors and three-dimensional core power distributions are computed for the first-cycle core of the YGN 3 PWR. The results are compared with predictions of the COLSS(Core Operating Limit Supervisory System) which is the axial power shape monitoring program of the YGN 3. It is shown that the modified Borresen's method can reproduce the core axial power shape more closely than the COLSS. Because of other advantages in computing speed and predictive capability, we conclude that the proposed MBSN has a promising practical application for core power distribution monitoring program development.

요 약

이 논문에서는 영광 3호기와 같이 노심내 핵계장 장치를 갖고 있는 가압형 원자력 발전소용 노심출력분포 감시프로그램의 개발에 수정형 Borresen 모형의 응용 타당성을 검토해 보았다. 이를 위해 수정형 Borresen 방정식의 소격모형해를 핵계장장치의 측정치를 경계조건으로 하여 풀었으며, 이로부터 영광 3호기 첫주기 노심의 3차원 출력분포를 계산하였다. 그 결과는 현재 영광 3호기의 축방향 출력분포 감시 프로그램으로 활용되고 있는 COLSS 예측치와 비교하였으며, 이를 통하여 수정형 Borresen 모형으로 제안한 방법이 COLSS 보다 축방향 출력분포를 실제에 더 가깝게 모사할 수 있음을 보였다. 노심 출력 거동에 대한 예측능력이 있고 또한 전산속도면에서의 이점이 있어서 제안된 수정형 Borresen 방법이 노심출력분포 감시프로그램 개발에 유용하게 활용될 수 있다고 결론을 내렸다.

1. Introduction

This work examines the feasibility of the direct use of modified Borresen's coarse-mesh diffusion theory method[1)] with the fixed in-core detector signals as core internal boundary conditions for developing an improved power distribution monitoring system program of PWR's. The Yonggwang unit 3(YGN 3)[2)], an ABB-CE PWR plant to be commissioned soon in Korea, uses the core monitoring system called the COLSS (Core Operating Limit Supervisory System)[3)] which calculates the axial power distribution by Fourier fitting method of the Rhodium detector signals. The fitting method which does not rely on the group diffusion equations has the advantage of fast prediction for axial power distributions. Yet it is not accurate for certain axial power shapes such as saddle power shapes[4,5)], it requires a pre-determined planar radial power distribution to compute three-dimensional power distribution, and it lacks predictive capability on core power shape following core maneuvering. This work is designed to seek for an improved method without these deficiencies.

The YGN 3 PWR has fixed Rhodium in-core detectors installed at so-called instrumented fuel assembly(FA) sites. The Rhodium detectors[6)] generate self-powered electric current proportional to the absorption rate of neutrons by the isotope Rh-103. The detector current readings can be converted to the nodal powers of the instrumented FA segments using pre-calculated proportionality constants between the current and the nodal power of the instrumented FA segment. Instead of fitting the detector signals to Fourier series[3)] or interpolation polynomials[4,5)], the proposed method consists of using them as core internal boundary conditions and solving directly coarse-mesh group diffusion equations for uninstrumented nodes, as suggested originally in Reference 7 for CANDU-PHWR.

For an effective power distribution monitoring system program, the speedy and accurate computation of three-dimensional power distributions from the detector readings is essential. In order to meet this, we consider in this paper the modified Borresen's coarse mesh diffusion theory method which has proved to be one of efficient coarse-mesh schemes for three-dimensional core power and criticality computations in LWR.[1)] In the following section we will give a brief description on the utilization of the modified Borresen's method, and demonstrate its qualification in terms of computational speed and accuracy, for core power distribution monitoring program for YGN 3 PWR.

2. Description of Method

The central principle of Borresen's coarse-mesh method[8)] consists of the first-order finite difference representation of the neutron current by the point fluxes and the interpolation formula for the node average group flux, $\bar{\phi}_{gi}$,

$$\bar{\phi}_{gi} = b_g \phi_{gi} + 2c_g \Big(\sum_{4j} \phi'^{j}_{gi} + R_i \sum_{2j} \phi'^{j}_{gi} \Big) ; \qquad (g=f,\, t) \quad (1)$$

where

$R_i = (\frac{h_{zi}}{h_{xi}})$,

h_{ui} $(u, = x, y, z)$ = the width of rectangular node i,

ϕ_{gi} = the group g neutron flux at the center of the rectangular node i,

b_g , c_g = empirical constants,

and the nodal interface group flux ϕ'^{j}_{gi} is given by

$$\phi'^{j}_{gi} = \frac{D_{gi} h_{uj} \phi_{gi} + D_{gj} h_{ui} \phi_{gj}}{D_{gi} h_{uj} + D_{gj} h_{ui}} \qquad (u = x, y, z). \quad (2)$$

Formulating the fast group nodal balance equation based on this principle, we obtain the coarse-mesh finite difference relations for the fast group diffusion density, $\psi_n = \sqrt{D_{fn}} \cdot \phi_{fn}$

$$Q_n \psi_n - \sum_{4m} \psi_m - R_n \sum_{2l} C^{l}_{n} \psi_{nl} = \frac{1}{k_{eff}} S_n \qquad (3)$$

where

$$Q_n = \frac{p_n + q_n(b_f + c_f r_n)}{1 - c_f q_n},$$

$$C_n^l = \frac{2\sqrt{D_{fn}}\sqrt{D_{fl}}}{\frac{h_{zl}}{h_{zn}} D_{fn} + D_{fl}}, \qquad q_n = \left(\frac{\Sigma_{tn}}{D_{fn}}\right) h_x^2,$$

$$p_n = \sum_{4m}\left(\frac{\sqrt{D_{fm}}}{\sqrt{D_{fn}}}\right) + R_n \sum_{2l}\left(\frac{2\frac{D_{fl}}{h_{zl}}}{\frac{D_{fn}}{h_{zn}} + \frac{D_{fl}}{h_{zl}}}\right),$$

$$r_n = \sum_{4m}\left(\frac{\sqrt{D_{fn}}}{\sqrt{D_{fm}}}\right) + R_n \sum_{2l}\left(\frac{2\frac{D_{fn}}{h_{zn}}}{\frac{D_{fn}}{h_{zn}} + \frac{D_{fl}}{h_{zl}}}\right),$$

and

$$S_n = \frac{h_x^2}{(1 - c_f q_n)\sqrt{D_{fn}}} \cdot \left(\nu\Sigma_{fn}\overline{\phi}_{fn} + \nu\Sigma_{ftn}\overline{\phi}_{tn}\right).$$

The third term in Eq. (3) differs slightly from the original difference relations in Ref. 8 because non-uniform axial nodes are taken. In this conjunction, one must note that division of the active core height by uniform axial nodes are not generally allowed because of the presence of the fixed in-core detectors.

The source term in Eq. (3) contains node average thermal group flux. In the modified Borresen's method[1)], the interpolation formula similar to Eq. (1) is assumed for $\overline{\phi}_{ti}$;

$$\overline{\phi}_{ti} = b_{ti}\phi_{ti} + 2c_{ti}\left(\sum_{4j}\phi_{ti}^j + R_i \sum_{2j}\phi_{ti}^j \right) \tag{4}$$

where

ϕ_{ti} = thermal group flux at the center of node i,

ϕ_{ti}^j = thermal group flux at the interface between node i and j.

In the spirit of the modified Borresen's method[1)], these are obtained by

$$\phi_{ti} = \left(\frac{\Sigma_{ri}}{\Sigma_{ati}}\right)\overline{\phi}_{fi} \tag{5}$$

and

$$\phi_{ti}^j = \frac{\frac{D_{ti}x_i}{T_i}\phi_{ti} + \frac{D_{tj}x_j}{T_j}\phi_{tj}}{\frac{D_{ti}x_i}{T_i} + \frac{D_{tj}x_j}{T_j}} \tag{6}$$

where

$$x_i = \sqrt{\frac{\Sigma_{ati}}{D_{ti}}},$$

$$T_i = \tanh\left(\frac{x_i h_{ui}}{2}\right); \qquad u = x, y, z.$$

With the thermal group flux determined this way, all one has to do in the core design computation is to solve Eq. (3) for all core nodes. In the core power monitoring application, however, the source term of Eq. (3) at the instrumented FA nodes is modified because it is related to incore detector current reading. In the YGN 3 where the fixed Rhodium incore detectors are utilized, electric current signal which is proportional to the absorption rate of neutrons by Rhodium isotope Rh-103 at the detector location is produced. With the pre-calculated conversion factors, the detector current signal is converted to the nodal power of each instrumented FA segment node, which in turn becomes the input of the COLSS. With such a nodal power information available, the source term at the instrumented FA segment node becomes

$$S_n^d = \frac{h_x^2}{(1 - c_n q_n)\sqrt{D_{fn}}} \times \left(\frac{\nu\Sigma_{fn}\left(\frac{\overline{\phi}_{fn}}{\overline{\phi}_{tn}}\right)_d + \nu\Sigma_{ftn}}{\chi\Sigma_{fn}\left(\frac{\overline{\phi}_{fn}}{\overline{\phi}_{tn}}\right)_d + \chi\Sigma_{ftn}} \right) \cdot P_n^d \tag{7}$$

where the P_n^d is nodal power converted from detector current signal. The thermal-to-fast flux ratio at the instrumented FA segment node, $(\overline{\phi}_{fn}/\overline{\phi}_{tn})_d$, can be precomputed like the conversion factor between the detector current and the instrumented FA segment nodal power.

In the application of the modified Borresen's scheme for core power shape monitoring program, one has to solve Eq. (3) with the known source term Eq. (7), i.e., core internal boundary conditions provided by the incore detector. In the following we will examine the applicability of the modified Borresen's coarse-mesh scheme for core power distribution monitoring computation in YGN 3 core.

3. Numerical Results and Discussion

The YGN 3 is the ABB-CE PWR plant of 1000MW(e) which is soon commissioned in Korea. The PWR core consists of 177 fuel assemblies. Figure 1 displays the location of fixed incore Rhodium detectors installed at 45 FA sites in five axial levels. Since the incore detector measurements for YGN 3 are not yet available, four-node-per-FA nodal expansion method(NEM) computations are performed to obtain the simulated (reference) three-dimensional full core power distributions in the first cycle core of YGN 3 PWR.

Figure 2 compares the axial power distributions from the COLSS and the modified Borresen's method(MBSN) computations with the reference power distribution in the first-cycle-core of YGN 3. In the MBSN computations, one-node-per-FA scheme was used. The nodal power of the instrumented FA segment node,P^d_n, to be fed up from the detector current signal is simulated by reading the nodal powers of the nodes representing instrumented FA segments from the reference power distribution. Figure 2 shows that the power monitoring computation by the MBSN is superior to the COLSS in reproducing the axial power shapes, particularly asymmetrical axial power shapes such as saddle power shapes developed at the middle-of-the-cycle(MOC) and the end-of-the-cycle(EOC).

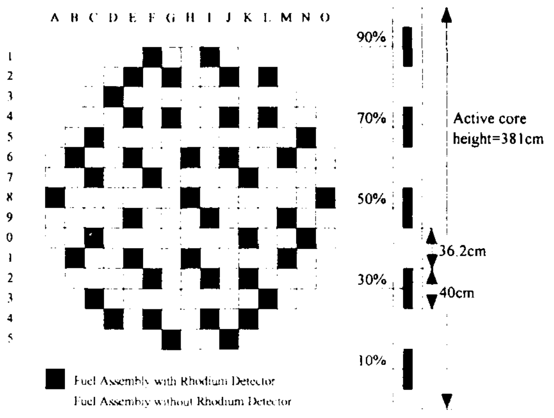

Fig. 1. Fixed Rhodium Detector Location

Figure 3 further compares the assemblywise normalized power distributions with one-node-per-FA MBSN computations with and without use of the simulated detector readings as core internal boundary conditions with the reference power distribution. Table 1 summarizes the relative normalized power errors. These results demonstrate that the power monitoring computation by the MBSN reproduces more closely the reference assemblywise power distribution than the MBSN computations without using simulated detector readings.

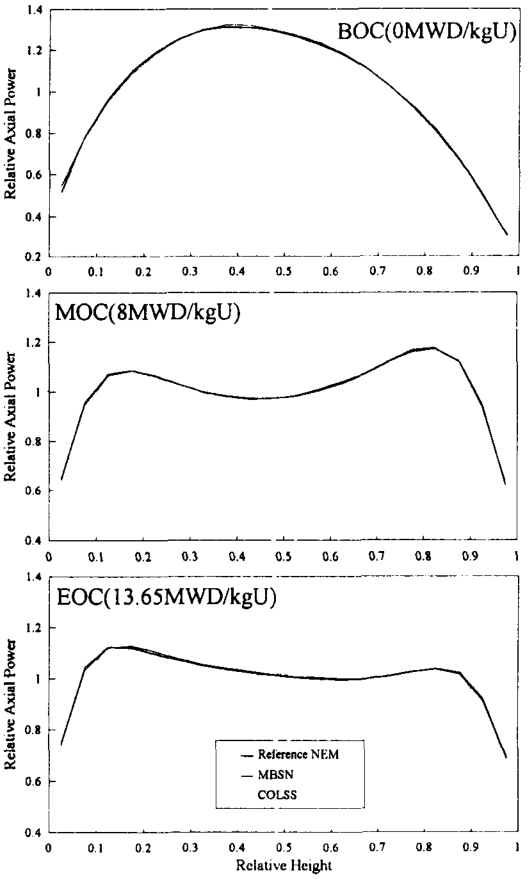

Fig. 2. Comparison of Core Average Axial Power Distributions at BOC, MOC, and EOC in the first cycle core of YGN 3 PWR.

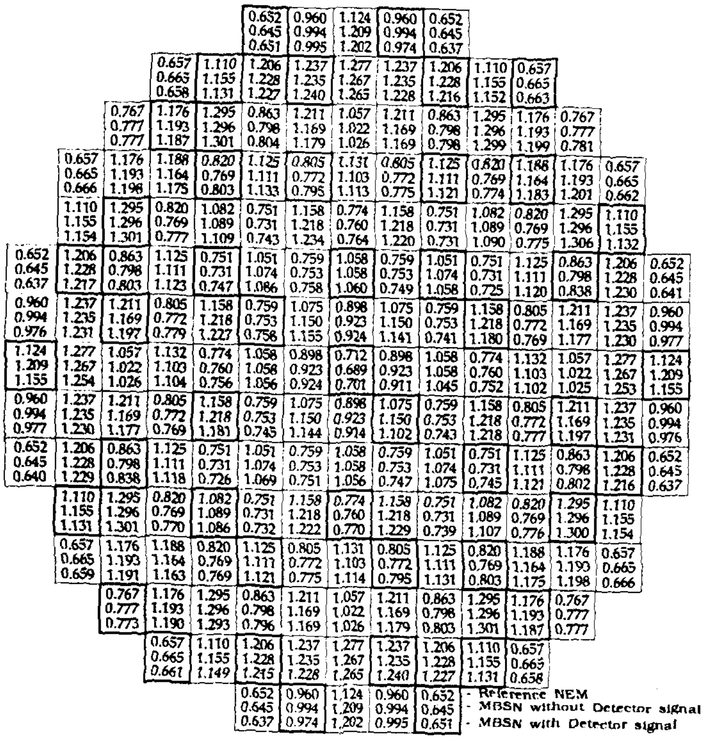

Fig. 3. (c) Normalized Assemblywise Power Distribution at EOC of the first cycle core of YGN 3 PWR

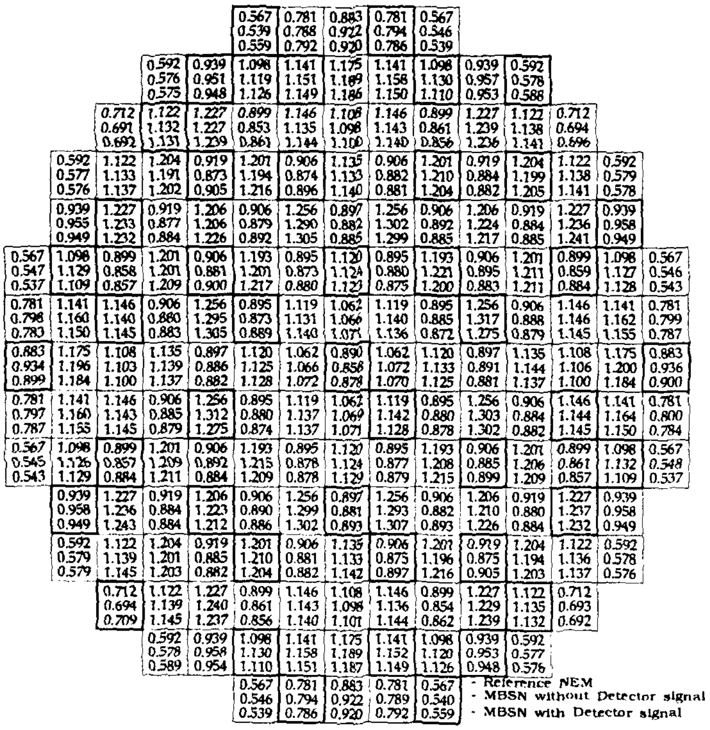

Fig. 3. (b) Normalized Assemblywise Power Distribution at MOC of the first cycle core of YGN 3 PWR

					0.581 0.556 0.575	0.773 0.775 0.780	0.858 0.887 0.887	0.773 0.782 0.777	0.580 0.565 0.559					
			0.599 0.587 0.588	0.918 0.920 0.924	1.065 1.079 1.088	1.093 1.097 1.098	1.116 1.124 1.123	1.093 1.105 1.099	1.065 1.093 1.075	0.918 0.927 0.923	0.599 0.589 0.597			
		0.708 0.692 0.693	1.076 1.087 1.085	1.179 1.178 1.190	0.920 0.882 0.890	1.119 1.110 1.118	1.083 1.077 1.079	1.119 1.119 1.116	0.920 0.893 0.886	1.179 1.191 1.187	1.076 1.091 1.093	0.708 0.694 0.695		
	0.599 0.589 0.588	1.076 1.088 1.090	1.158 1.149 1.159	0.943 0.905 0.932	1.192 1.186 1.204	0.946 0.919 0.939	1.136 1.135 1.140	0.946 0.930 0.927	1.192 1.205 1.196	0.943 0.919 0.916	1.158 1.157 1.159	1.076 1.090 1.093	0.599 0.590 0.590	
	0.918 0.926 0.920	1.179 1.186 1.184	0.943 0.911 0.917	1.201 1.200 1.216	0.956 0.932 0.944	1.263 1.287 1.299	0.954 0.940 0.942	1.263 1.301 1.297	0.956 0.948 0.940	1.201 1.220 1.212	0.943 0.918 0.918	1.179 1.186 1.191	0.918 0.926 0.924	
0.580 0.567 0.558	1.065 1.093 1.074	0.920 0.889 0.887	1.192 1.195 1.201	0.956 0.934 0.950	1.211 1.215 1.228	0.958 0.938 0.944	1.149 1.153 1.151	0.958 0.947 0.942	1.211 1.238 1.217	0.956 0.951 0.939	1.192 1.204 1.202	0.920 0.886 0.908	1.065 1.086 1.089	0.580 0.564 0.562
0.773 0.787 0.774	1.093 1.108 1.098	1.119 1.116 1.118	0.946 0.927 0.928	1.263 1.292 1.300	0.958 0.938 0.952	1.150 1.156 1.164	1.101 1.103 1.107	1.150 1.167 1.162	0.958 0.952 0.940	1.263 1.318 1.279	0.946 0.935 0.927	1.119 1.120 1.119	1.093 1.107 1.101	0.773 0.786 0.776
0.858 0.901 0.872	1.116 1.132 1.122	1.083 1.081 1.078	1.136 1.142 1.139	0.954 0.945 0.940	1.149 1.153 1.155	1.101 1.102 1.107	0.960 0.933 0.950	1.101 1.109 1.107	1.149 1.162 1.154	0.954 0.950 0.940	1.136 1.147 1.139	1.083 1.084 1.079	1.116 1.135 1.122	0.858 0.903 0.872
0.773 0.785 0.776	1.093 1.104 1.101	1.119 1.117 1.119	0.946 0.932 0.926	1.263 1.312 1.279	0.958 0.947 0.941	1.150 1.162 1.162	1.101 1.105 1.107	1.150 1.168 1.156	0.958 0.946 0.943	1.263 1.300 1.299	0.946 0.931 0.928	1.119 1.120 1.118	1.093 1.110 1.098	0.773 0.789 0.774
0.580 0.563 0.562	1.065 1.084 1.089	0.920 0.884 0.908	1.192 1.201 1.202	0.956 0.947 0.939	1.211 1.230 1.224	0.958 0.944 0.943	1.149 1.152 1.156	0.958 0.942 0.944	1.211 1.222 1.227	0.956 0.938 0.950	1.192 1.199 1.201	0.920 0.892 0.887	1.065 1.096 1.075	0.580 0.568 0.558
	0.918 0.925 0.924	1.179 1.185 1.192	0.943 0.917 0.917	1.201 1.219 1.207	0.956 0.944 0.940	1.263 1.296 1.298	0.954 0.938 0.949	1.263 1.288 1.301	0.956 0.935 0.944	1.201 1.203 1.217	0.943 0.914 0.917	1.179 1.189 1.184	0.918 0.928 0.921	
	0.599 0.589 0.591	1.076 1.089 1.096	1.158 1.158 1.160	0.943 0.919 0.915	1.192 1.203 1.196	0.946 0.927 0.928	1.136 1.133 1.142	0.946 0.919 0.939	1.192 1.187 1.204	0.943 0.906 0.933	1.158 1.152 1.159	1.076 1.090 1.090	0.599 0.591 0.588	
		0.708 0.691 0.705	1.076 1.090 1.095	1.179 1.190 1.188	0.920 0.891 0.887	1.119 1.118 1.116	1.083 1.075 1.079	1.119 1.109 1.118	0.920 0.882 0.891	1.179 1.179 1.190	1.076 1.088 1.085	0.708 0.693 0.693		
			0.599 0.589 0.597	0.918 0.926 0.923	1.065 1.092 1.075	1.093 1.104 1.099	1.116 1.123 1.123	1.093 1.096 1.098	1.065 1.079 1.088	0.918 0.921 0.924	0.599 0.588 0.588			
					0.580 0.565 0.559	0.773 0.782 0.777	0.858 0.887 0.887	0.773 0.775 0.780	0.580 0.556 0.575					

- Reference NEM
- MBSN without Detector signal
- MBSN with Detector signal

Fig. 3. (c) Normalized Assemblywise Power Distribution at EOC of the first cycle core of YGN 3 PWR

Table 1. Summary of Assemblywise Relative Power Errors

Method & Error(%)	Core state (MWD/kgU)	BOC (0)	MOC (8)	EOC (13.65)
MBSN without	$\varepsilon_{\max}{}^{1)}$	7.5	6.0	5.1
detector signal	$\varepsilon_{\text{avg}}{}^{2)}$	2.7	2.0	1.5
MBSN with	$\varepsilon_{\max}$	7.7	5.2	3.8
detector signal	ε_{avg}	2.2	1.6	1.2

1) $\varepsilon_{max}(\%) = \max\left|\dfrac{P_{ref}-P_i}{P_{ref}}\right| \times 100; (i=1, \cdots, N_{Assembly})$.

2) $\varepsilon_{max}(\%) = \dfrac{1}{N_{Assembly}} \sum_{i=1}^{N_{Assembly}} \left|\dfrac{P_{ref}-P_i}{P_{ref}}\right| \times 100.$

4. Conclusions

The MBSN method proposed above may run on the plant computer or a dedicated on-line workstation with pre-computed input data such as the node average fast-to-thermal flux ratio at the instrumented FA segment nodes and nodal power conversion factors from incore detector current signals. The CPU time required for the computation of three-dimensional full core power shape by the MBSN is less than 2 seconds on HP-735 workstations, which is fast enough for the purpose of the power distribution monitoring. In addition to core power distribution monitoring, the proposed MBSN method could also be utilized as a predictive method for core power and xenon spatial behavior followed by control actions including control rod movements, boron concentration changes, etc. Therefore, we conclude that the proposed MBSN method may have promising practical applications.

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