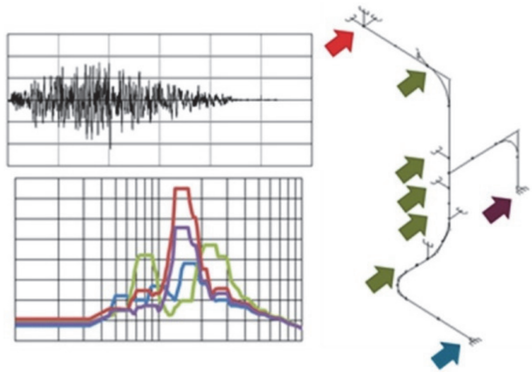
Floor Response Spectrum Method Assisted by Time History Analysis to Rationalize Seismic Design for Multiply Supported Piping System



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There are two seismic design methods for piping systems- time history analysis, which is a detailed method, and floor response spectrum analysis, which is a simplified method. In general, the floor response spectrum analysis method is used in design. However, since the floor response spectrum analysis method does not include phase information, it sometimes results in overestimation compared to the detailed time history analysis method. Then, as a different approach from previous analysis methods, Mitsubishi Heavy Industries, Ltd. has developed a floor response spectrum analysis method that uses correlation coefficients to combine the response by each seismic excitations wave to achieve almost the same accuracy as that by the time history analysis method. This analysis method has been publicized through presentations at academic conferences such as the Pressure Vessels & Piping Conference, and aims for application in actual plants.

1. Introduction

Piping systems for nuclear power plants must be seismically designed to ensure that the surrounding public is not exposed to radiation hazards even if a major earthquake occurs during the plant's service life. As a seismic response analysis method for piping systems subjected to different excitations from each individual support point, uniform support motion spectrum analysis using enveloped spectra is widely used. However, this method can be too conservative. One alternative method is an independent support motion spectrum analysis, but the method to combine responses for multiple excitations is controversial. When the method to combine responses for multiple excitations is the absolute sum (hereinafter referred to as ABS) rule, it is always conservative and may derive considerable overestimation. When the square root of sum of squares (hereinafter referred to as SRSS) rule is used, it may not always be conservative and then, it is difficult to use the SRSS method unconditionally without confirming its applicability. Since the ABS method may result in overly conservative results, Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) has developed a new method called the spectrum method assisted by time history analysis (hereinafter referred to as SATH), which is different from ABS and SRSS methods, to calculate more realistic responses in independent support motion analysis. By applying SATH method, more appropriate scale of facilities and construction work are expected to be possible.

2. About the SATH method

Three kinds of responses are generated in the piping system subjected to different seismic excitations from each support point: (1) dynamic response which is dynamic modal response for each vibration mode of the piping system, (2) high frequency response which is dynamic response for higher order vibration mode, and (3) pseudo static response which is relative displacement response by support point displacement.

In conventional response analysis of piping systems, the SRSS or ABS method is used to combine the maximum response for dynamic response, high frequency response, and pseudo static response. However, SATH method combines all these maximum responses based on the correlation

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coefficient. A comparison of response combining methods of the conventional spectrum analysis method and SATH method is shown in **Figure 1**. In the conventional spectrum analysis method (uniform support motion spectrum analysis method and independent support motion spectrum analysis method), dynamic response, high frequency response, and pseudo static response are combined after individual responses are combined due to excitation from each support group. In contrast, the SATH method combines the all individual responses, taking into account the correlation coefficients among the individual dynamic responses, high frequency responses, and pseudo static responses by excitation from each support group. This is to ensure the appropriate response combination that takes the phase into account. The conventional uniform support motion or the independent support motion spectrum analysis method often yields overly conservative results, whereas SATH method can calculate nearly identical results to time history analysis, which are considered to be correct.

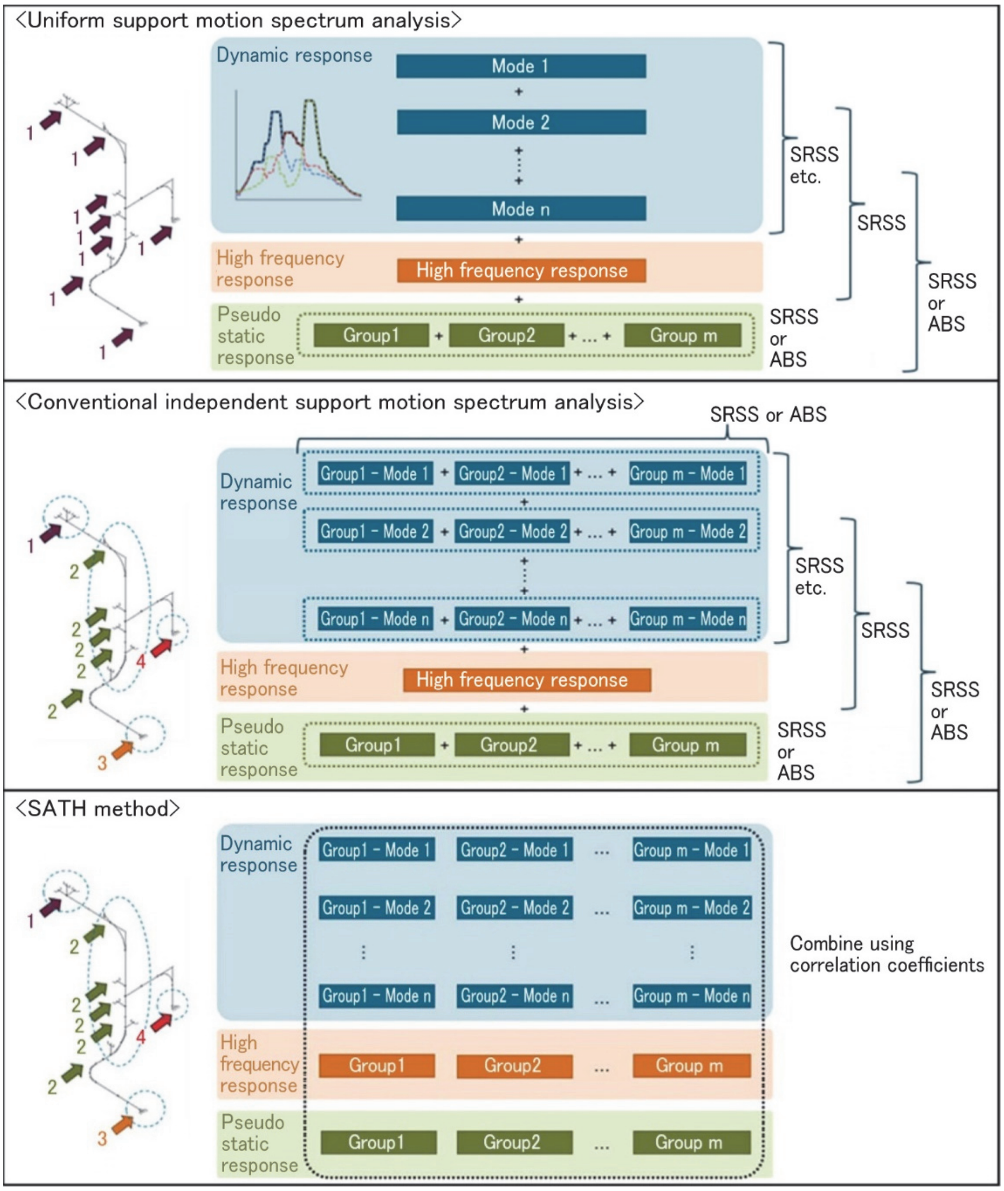

Figure 1 Diagram of the combination method
The combination method of dynamic response, high frequency response, and pseudo static response for each analysis method is shown.

2.1 Combination method using correlation coefficients

Assuming that the total number of excitations acting on the piping system from each support point is m and the total number of modes, up to the cutoff frequency in the response spectrum analysis of the piping system, is n, the piping system will have a dynamic response to each excitation for each mode, resulting in a total $m \times n$ modal responses. In addition, a total of m high frequency responses are generated for each excitation. Furthermore, each excitation causes building displacement, and these building displacements produce a total of m pseudo static responses in the piping system. These responses are shown in **Table 1**.

Table 1 Dynamic response and static response

			Excitations from different building floors (total number m)						
		No.	1	...	k	...	l	...	m
Dynamic response	Modal response (total number n)	1	${}_DR_{11}$	...	${}_DR_{1k}$	...	${}_DR_{1l}$		${}_DR_{1m}$
		...	...	...	...	...	...	...	...
		i	${}_DR_{i1}$	...	${}_DR_{ik}$	...	${}_DR_{il}$		${}_DR_{im}$
		...	...	...	...	...	...	...	...
		j	${}_DR_{j1}$	...	${}_DR_{jk}$	...	${}_DR_{jl}$		${}_DR_{jm}$
		...	...	...	...	...	...	...	...
		n	${}_DR_{n1}$	...	${}_DR_{nk}$	...	${}_DR_{nl}$		${}_DR_{nm}$
	High frequency response	$n+1$	${}_HR_1$	...	${}_HR_k$	...	${}_HR_l$		${}_HR_m$
Static response	Pseudo static response	$n+2$	${}_SR_1$	...	${}_SR_k$	...	${}_SR_l$		${}_SR_m$

In Table 1, there are n modal responses, one high frequency response, and one pseudo static response corresponding to m excitations, so Table 1 has a matrix of $(n+2)\times m$. In this matrix, maximum value of the response in row i, column k is defined as R_{ik}. R_{ik} includes all dynamic responses, high frequency responses, and pseudo static responses, where $1 \le i \le n+2, 1 \le k \le m$. Assuming that the correlation coefficient between the responses R_{ik} and R_{jl} is ρ_{ikjl}, the total stress of the dynamic response, high frequency response, and pseudo static response for all excitations can be obtained using the correlation coefficient as follows.

$$R = \sqrt{\sum_{i=1}^{n+2}\sum_{j=1}^{n+2}\sum_{k=1}^{m}\sum_{l=1}^{m}\rho_{ikjl}R_{ik}\,R_{jl}}$$

Correlation coefficient ρ_{ikjl} is obtained from the following equation, where $X_{ik}(s)$ is the displacement time history of each response in Table 1 (s represents a time step, and the total number of time steps is N).

$$\rho_{ikjl} = \frac{\sum_{s=1}^{N} X_{ik}(s)X_{jl}(s)}{\sqrt{\sum_{s=1}^{N}\left(X_{ik}(s)\right)^2}\sqrt{\sum_{s=1}^{N}\left(X_{jl}(s)\right)^2}}$$

The displacement time history $X_{ik}(s)$ of each response used to calculate the correlation coefficient is as follows.

(i) Dynamic response:
The time history response displacement $X_{ik}(s)$ can be obtained by the time history analysis of an oscillator having the i-th mode frequency of piping system using the k-th floor time history acceleration.

(ii) High frequency response:
Since the high frequency response is a rigid-body response, the response displacement time history is proportional to the input acceleration time history. When calculating the correlation coefficient, the value of the correlation coefficient is the same even if the time history values are multiplied proportionally. Therefore, input acceleration time history is considered to be the response displacement time history $X_{(n+1)k}(s)$.

(iii) Pseudo static response: Since pseudo static response is a static response, the response displacement time history is proportional to the input displacement time history. When calculating the correlation coefficient, the value of the correlation coefficient is the same even if the time history values are multiplied proportionally, so input displacement time history is considered to be the response displacement time history $X_{(n+2)k}(s)$.
The flow of the SATH method is shown in **Figure 2**.

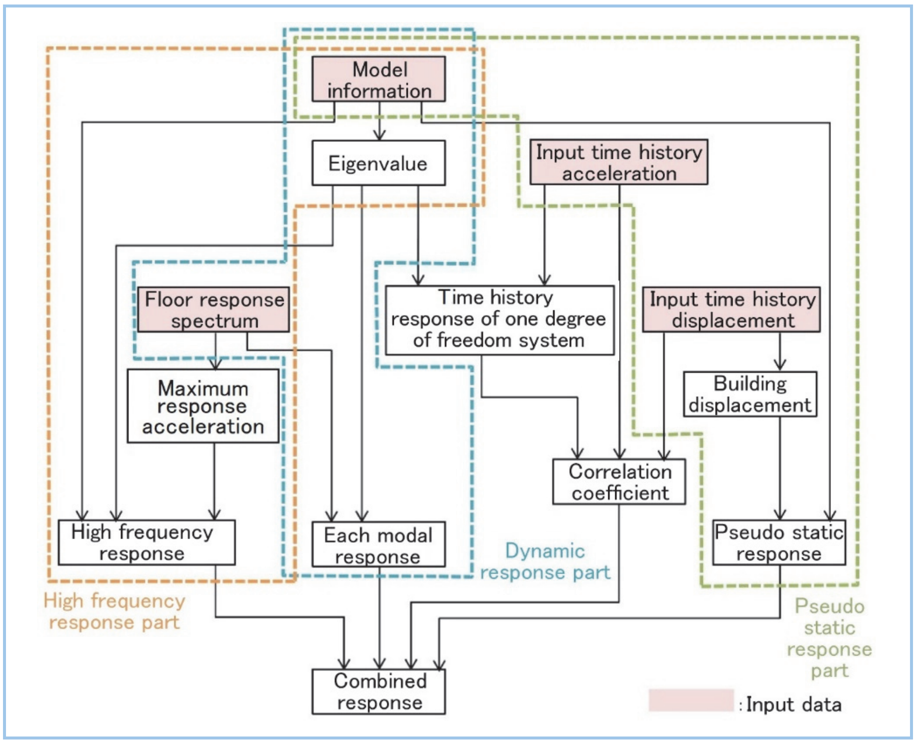

Figure 2　Flow diagram of the SATH method
The flow of SATH method is shown.

3. Result of analysis using SATH method

To confirm the effectiveness and advantages of SATH method, seismic response analyses of a multiply supported piping system subjected to independent excitations were performed using several analysis methods, and the results of SATH method were compared with those of the independent support motion modal time history analysis (hereinafter referred to as TH) method and conventional response spectrum analysis methods. The conventional response spectrum analysis methods used were the independent support motion response spectrum analysis (hereinafter referred to as ISM) method and the uniform support motion response spectrum analysis (hereinafter referred to as USM) method. Analysis cases are shown in **Table 2**.

Table 2　Analysis cases

Analysis method	Response combination method			
	Combination between multiple excitations	Modal Combination	Combination with high frequency response	Combination with pseudo static response
TH	Algebraic sum at each time step			
SATH	Combination using correlation coefficients			
ISM	ABS	SRSS	SRSS	SRSS
USM	-	SRSS	SRSS	ABS

3.1 Analysis conditions

The 3D piping system model used in the analysis is shown in **Figure 3**. This model was taken from the NUREG/CR-1677 benchmark problem for piping systems subjected to different excitations from multiple points[1]. Acceleration time history, floor response acceleration spectrum (hereinafter referred to as FRS), and the building analysis model are shown in **Figures 4, 5, and 6**, respectively. As shown in Figure 5, in order to consider the structural frequency uncertainty, the floor response acceleration spectrum used was broadened by 10%. And for TH analysis, the calculation with the scaled time interval corresponding to the calculation with broadened FRS was carried out. The broadening range was divided into 8 portions, and the calculation of the total 9 cases, with 0%, ±2.5%, ±5.0%, ±7.5%, and ±10% scaled time interval, was carried out.

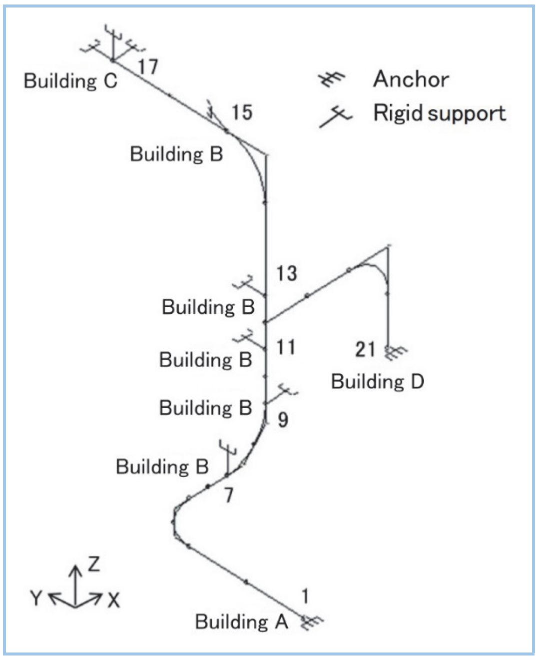

Figure 3 Analysis model
The 3D beam model of the piping system used in the analysis is shown.

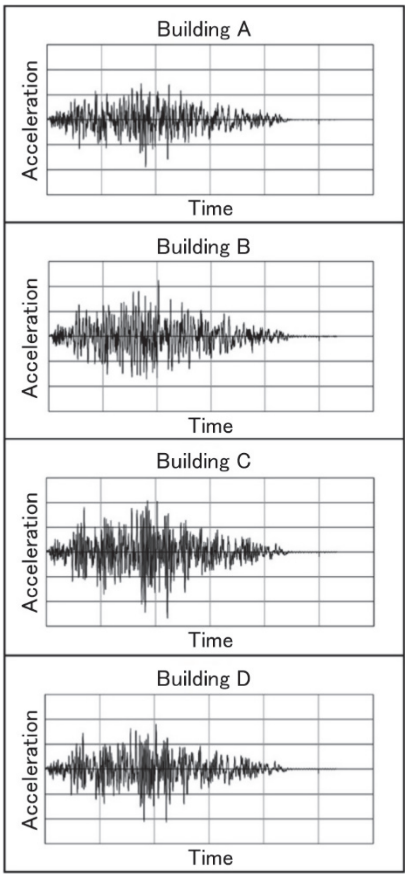

Figure 4 Time history acceleration
The acceleration time history waveforms input to the analysis model are shown.

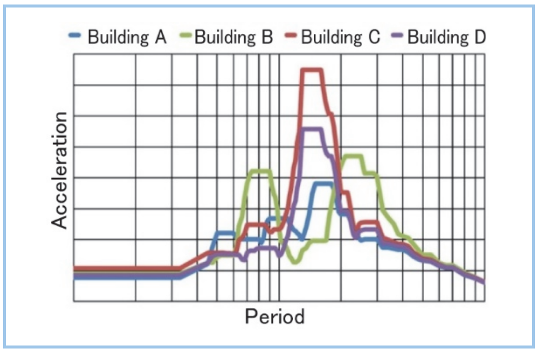

Figure 5 Floor response acceleration spectrum
The floor response acceleration spectrum input to the analysis model is shown.

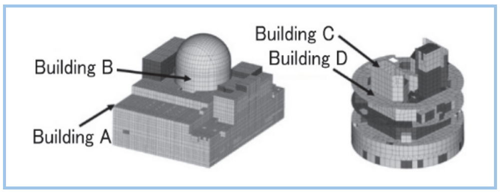

Figure 6 Building analysis model
The building analysis models with the building names are shown.

3.2 Analysis results

A comparison of the support reaction forces as a result of analysis of each case is shown in **Figure 7**. The figure on the left shows (1) dynamic response only, the figure in the center shows the combination of (1) dynamic response and (2) high frequency response, and the figure on the right shows the combination of (1) dynamic response, (2) high frequency response, and (3) pseudo static response.

First, in the figure on the left, SATH method is in good agreement with TH method. However, results from ISM method and USM method were overestimations compared to SATH method and TH method. In particular, the support reaction forces in cases No. 7 and No. 15 were approximately twice as large as those from SATH method and TH method.

Also in the figure in the center, SATH method is in good agreement with TH method. Compared to the figure on the left, support reaction forces in No. 9 are smaller. This is a result of the combination of (1) dynamic response and (2) high frequency response, where their reaction forces cancel each other out due to the opposite phase effect. This indicates that SATH method properly considers phase information.

Finally, in the figure on the right, SATH method is in good agreement with TH method again. Several support reaction forces results obtained from ISM method and USM method were approximately 2 to 3 times larger than those from SATH method and TH method.

From the above results, good agreement between SATH method and TH method could be confirmed in all cases. From this, SATH method can evaluate (1) dynamic response, (2) high frequency response, and (3) pseudo static response by combining appropriately, and can avoid excessive response compared to conventional methods, and can achieve almost the same analysis accuracy as the time history analysis method.

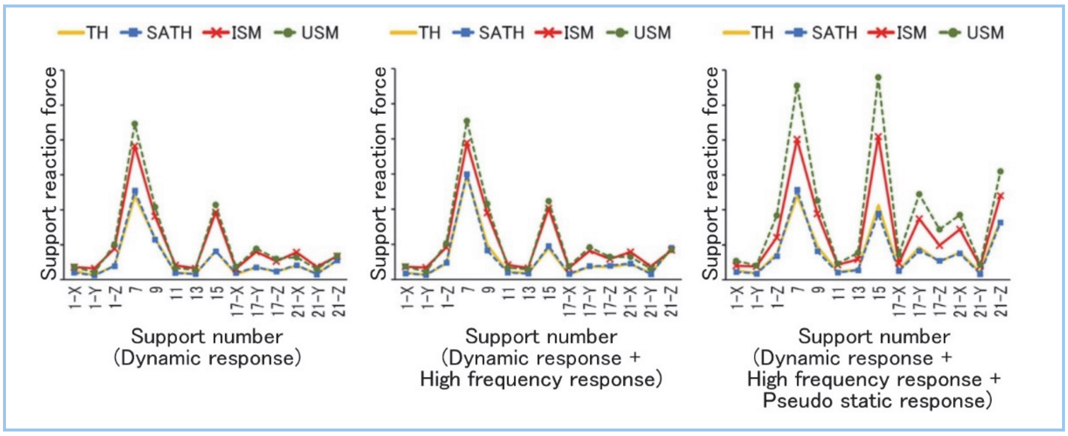

Figure 7 Analysis result (comparison of support reaction forces)
The comparison of conventional methods and SATH method using support reaction force analysis results is shown.

3.3 Advantages of SATH method

In the previous section, analysis accuracy of SATH method could be confirmed to be nearly equivalent to that of the TH method. Reasons for the superiority of SATH method over the TH method are as follows.

- The SATH method requires less computation time than TH method. This is especially true when the floor response acceleration spectrum is broadened to deal with the structural frequency uncertainty.
- Identifying dominant modes for appropriate support placement in piping systems is difficult when TH method is used. On the other hand, the dominant modes can be easily identified in the same way as the conventional response spectrum analysis method when SATH method is used.

4. Conclusion

MHI has been seeking greater reliability of nuclear power plants by improving seismic evaluation technology. This report presented a new seismic design method developed for piping in nuclear power plants. MHI will contribute to the increased safety of nuclear power plants, while continuing to improve and develop technologies and equipment.

References

(1) P. Bezler et al., Dynamic Analysis Independent Support Motion Response Spectrum Method, NUREG/CR-1677, U.S. Nuclear Regulatory Commission, Vol. 2, (1985) p.77-86