A mockup piping system damping evaluation and a simulation of the mockup piping vibration tests

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ABSTRACT
A mockup piping system vibration test was performed to investigate the piping system seismic damping ratio when the piping system vibrate with large displacement under strong earthquake conditions. The present paper describes evaluated mockup piping system damping ratios by analyzing vibration test data and a simulation for the vibration test. The mockup piping system used in this test was made of stainless steel and had 46.5-m. total length with 10-in. diameter. The simulations were performed to confirm the evaluated piping system vibration properties obtained in the present study by applying a linear structural analysis model.

1. INTRODUCTION

Japanese BWR nuclear power plant utilities and plant makers performed a mockup piping system vibration test, using two kinds of mockup piping systems (Category I piping system and Category II piping system), aiming at a survey of the piping system seismic damping ratio when the piping system vibrate with large displacement under strong earthquake condition. The present paper describes a piping system vibrational property analysis result, which is performed by analizing Category I piping system mockup vibration test data. The paper first describes an outline of a mockup piping system used in this vibration test. Second, it presents a comparison of damping ratios evaluated by several methods. Finally, results of a simulation study made for the random vibration test data to investigate the propriety of the evaluated damping values are presented.

2. MOCKUP PIPING SYSTEM VIBRATION TESTS

A mockup piping system used in this vibration test was made of stainless steel (STS42,schedule 40). This piping system consists of the main part, a branch part and two mockup valves. The main part pipe was 10-in. in diameter and the branch part pipe was 6-in. in diameter, respectively. Each part was filled with water. The total length of this piping system was 46.5-m. The mockup piping system was installed on the 15 x 15 meters shaking table. Figure 1 shows detailed dimensions of this piping system.

The mockup piping system was designed as a typical moderate diameter piping system, which are used widely in current nuclear power plants. This piping system had 10 support points. These piping system supports include seven guide frame restraint points, one spring hanger and two residual support points, which were changed (guide frame restraint, snubber or rod restraint) according to the test case. The vibration test data, analyzed in the present analysis, consists of swept sine vibration test data and random vibration test data. In these vibration tests, one directional vibrational motions were applied as input motions to the shaking table. The acceleration levels of the input vibrational motions were determined so that the maximum relative displacement of the piping system exceeded 20-mm. Then, 400 gal of an input acceleration level was assigned for swept sine vibration test as an input motions. For the random vibration test, maximum input accelerations were varied from 250 gal to 2200 gal. The random acceleration time history was made to have flat Fourier amplitudes property in the 1-33 Hz frequency range.

3.VIBRATIONAL PROPERTIES EVALUATION

Evaluated first and second natural frequencies of the mockup piping system, obtained from swept sine vibration tests for the different boundary conditions, are listed in Table 1. Figure 2 shows a typical first vibrational mode shape for the mockup piping system, evaluated from these test data. These natural frequencies are determined from transfer functions, which are evaluated by analyzing observed acceleration time histories on the center of the shaking table, together with observed acceleration time histories at a point on the piping system where maximum acceleration is observed. The damping ratios for this piping system are evaluated by applying the half power method and the curve fit method. The curve fit method applied here was proposed by Sato [2]. The feature of this method is in the way to evaluate resonance peak in a transfer function, which exclude the lobe effect of other peaks from the peak in remarking. This method requires only an imaginary part of a transfer function in its curve fitting process. In the evaluation of random vibration test data, the AR (Auto Regressive) method and the curve fit method were applied. The AR method applied here was proposed by Suzuki [3]. Natural frequencies and damping ratios for the multi-degree of freedom system can be evaluated directly by applying the AR method to a response time history observed on a point of the piping system. The applicability and effectiveness of the AR method to the piping system vibrational property evaluations are demonstrated by one of the authors [4]. Figure 3 demonstrates a typical transfer function and evaluated natural frequencies and damping factors for the mockup piping system which were obtained by applying the AR method to a test data. Figure 4 demonstrates an imaginary part of the transfer function, resultant fitted curve and evaluated natural frequency and damping ratio for the first vibrational mode, these were obtained by the curve fit method.

4. STATISTICAL ANALYSIS ON EVALUATED DAMPING RATIOS

In the present study, many damping factors were evaluated by analyzing various vibrational test data. One of the main purposes of the present vibration test is an investigation on the generic vibrational piping system damping property, when vibrational response displacement is large. Then, the evaluated damping values are analyzed statistically for each vibration test and evaluation method, regardless of the differeces in the boundary conditions of the piping system established for each test case, as is shown in Table 1. Though, not shown in the present paper, mutual differences which appeared in evaluated damping values for each test case had been confirmed to be very small. In general, the damping values for the piping system are normally distributed in the logarithmic scale. Then, in the present study, statistical analyses for the evaluated piping system damping ratios were made by assuming a log-normal distribution in these evaluated damping values. Figure 5 shows the statistical analysis results for the damping ratios obtained by the present analyses. Two kinds of averaged damping ratios are shown in this figure for the swept sine vibration test data. One is evaluated by applying the half power method and the other is evaluated by the curve fit method. For the random vibration test data, the evaluated average damping ratios by applying the AR method and by the curve fit method are also given.
In this figure, statistically analyzed damping values, i.e. the Av (averaged value), the Av + Sd (standard deviation) value and the Av + 2Sd value are demonstrated. The results are also tabulated in Table 2.

The averaged damping ratio for the 1-st vibrational mode of 5.6 Hz was estimated as 6 % from the results of the swept sine vibration test data, and as 8 % from the results of the random vibration test data. It can be seen in the swept sine vibration test results, that the difference between Av of the damping ratios, obtained by applying the half power method, and that obtained by applying the curve fit method, is very small. In the the random vibration test results, the difference between the Av of the damping ratio obtained by the AR method and that obtained by the curve fit method is also very small. The damping ratios, evaluated by analyzing random vibration test data, tend to have somewhat larger value than the ratios evaluated by analyzing swept sine vibration test data.

5. THE VIBRATION TEST SIMULATION

Simulation studies for this vibration test were performed to make a confirmation and a propriety evaluation for the present vibration property analysis for the mockup piping system. The random vibration test was considered to be favorable for this simulation study, because it had been performed by changing maximum acceleration value of the input acceleration time history (i.e., 6 or 7 levels for a test case) so that comparison between observed response vibration and simulated response vibration can be performed for various input vibration levels. Moreover, the input time history itself had short duration time. For these reasons, the simulation study was performed for the random vibration test data.

In the present simulation study, the mockup piping system is modeled to have 98 nodal points with 116 finite elements. The interaction effect between piping and guide frame restraint is represented by idealized spring, of which stiffness is determined by taking gap effects between piping and guide frames into account. The natural frequencies of this model evaluated by modal analysis are tabulated for the lower five vibrational modes in Table 3. Figure 7 shows subjective 1st vibrational mode of the simulation model. This vibrational mode shape can be considered to be closely matched to the observed one, which is shown in Fig 2. The acceleration time histories observed on the shaking table were used as the input vibrations to this simulation model. The vibrational response comparison between the simulation model and the test results were performed, with regard to the acceleration time history levels and their shapes at a nodal point, where the maximum seismic response was observed.

The following three damping ratios were applied in the simulation study.

(1) 2% damping ratio for all vibrational modes. (This is a current Japanese seismic design damping ratio for piping systems.)

(2) 8% for the first mode, 6% for the second mode and 2% for modes higher than third mode. (These are based on the Av values, evaluated from random vibration test data by applying the AR method.)

(3). 13% for the first mode, 12% for the second mode and 2% for all of the other modes. (These are based on the Av+2Sd values, evaluated damping ratios by AR method.)

The random vibration tests were simulated for each damping ratio model by changing input acceleration time histories. Maximum acceleration response values, obtained by these simulation results, are plotted as functions of input acceleration levels and shown in Fig.7 together with the observed values. It can be seen that the maximum acceleration values obtained by the simulation with the case (2) model, are closely matched to the observed maximum acceleration values. On the other hand, the maximum acceleration values obtained by applying the case (1) model of current seismic design damping ratios, considerably exceeds observed maximum acceleration values. In this figure, some safety margins in the current piping system design damping ratios can be seen. Figure 8 shows an example of the response acceleration time histories for the case in which maximum input acceleration is 1800 gal. The top left of this figure shows observed acceleration time history. Immediately below shows the simulated acceleration time history for the case (1) model. The top right and the bottom right also show the simulation results for the case (2) model and for the case (3) model respectively. It can be seen, that the acceleration time histories obtained by applying the case (2) and the case (3) damping ratios, have similar shape with the observed one. However, the acceleration time history, obtained by applying current seismic design damping ratio to the simulation model, is somewhat different in its shape from observed acceleration time history and has beat shapes which are peculiar to the response of a low damped vibration system.

6. CONCLUSIONS

The seismic damping ratio for a mockup piping system were evaluated by applying the half power method and the curve fit method to the swept sine vibration test data and by applying the curve fit method and the AR method to the random vibration test data. Simulation for the vibration test were also performed. The acceleration time histories obtained by the simulation, which applying averaged damping ratios, are closely matched to the observed records, both in their maximum values and shapes.

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Table.1 Dominant vibrational mode for each test case evaluated by swept sine vibration test data.

TEST CASE	First MODE(Hz)	SECOND MODE(Hz)
1	5.5	8.9
2	5.6	8.3
3	5.9	8.0
4	5.6	8.3
5	5.5	9.3

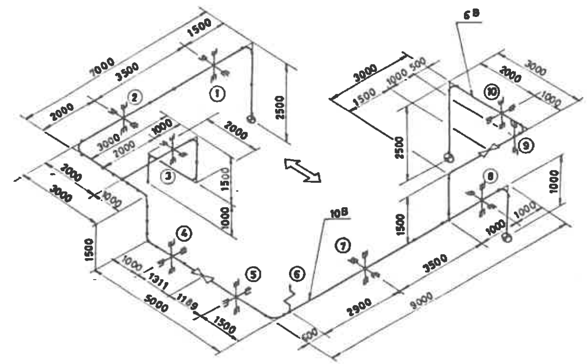
Table.3 Natural Frequencies of the analytical model for the mockup piping system.

VIBRATIONAL MODE	NATURAL FREQUENCY
1 st	6.0 Hz
2 nd	9.4 Hz
3 rd	9.8 Hz
4 th	14.2 Hz
5 th	20.3 Hz

Table.2 Evaluated Damping Values for the mockup piping system

(For the First vibrational mode)

	Swept Sine Vibration			Random Vibration		
	AV	Av-1Sd	Av-2Sd	Av	Av-1Sd	Av-2Sd
Half Power Method	6.4	5.1	4.1			
Curve Fit Method	6.1	5.0	4.0	9.1	7.4	6.0
AR Method				7.8	6.1	4.7



Diameter	Thickness	Material	Total Length	Insulation	Comment
10B (Branch 6B)	sch 40 (9.3mm)	STS42	46.5 meters	none	with Water

Figure 1. Detailed mockup piping system specification.

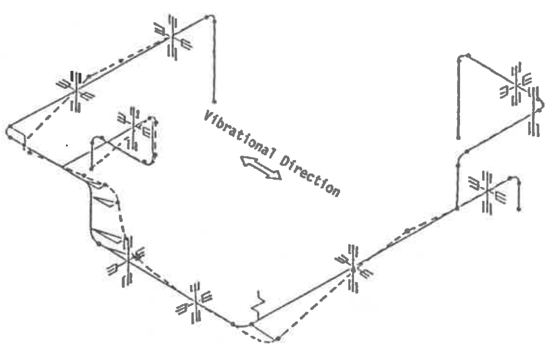


Figure 2. First vibrational mode, evaluated by test data analysis.

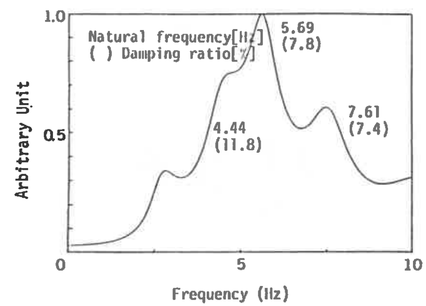


Figure 3. Example of evaluated natural frequencies and damping ratios of the mackup piping system by applying the AR method to a random vibration test data.

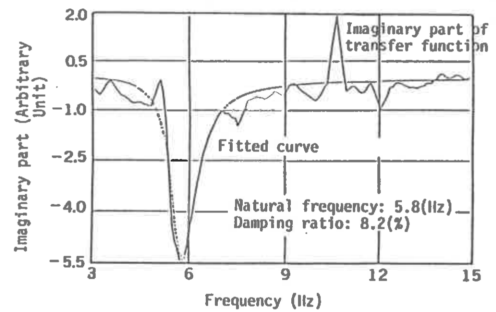


Figure 4. An example of the evaluated natural frequency and damping ratio of the mockup piping system by applying the curve fit method to a random vibration test data.

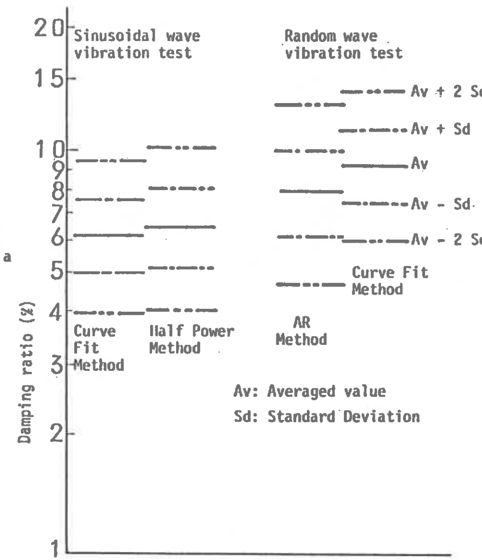


Figure 5. Comparison of statistically evaluated damping ratios obtained by three different evaluation methods.

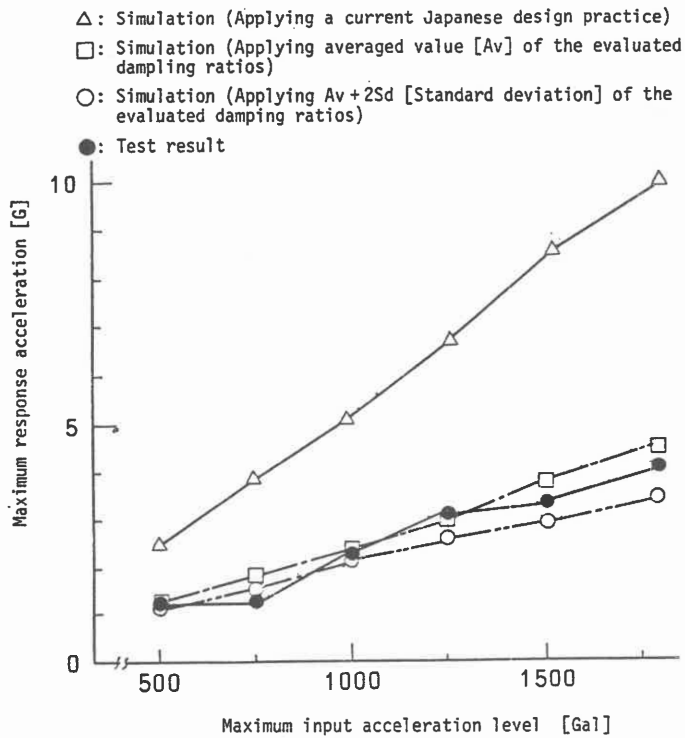


Figure 6. Comparison of simulated maximum response accelerations of the mockup piping system with the observed values.

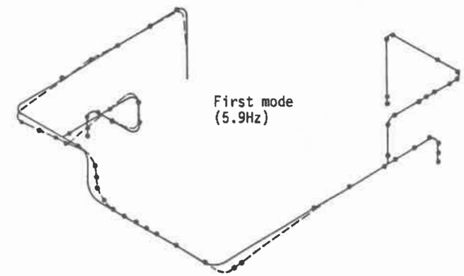
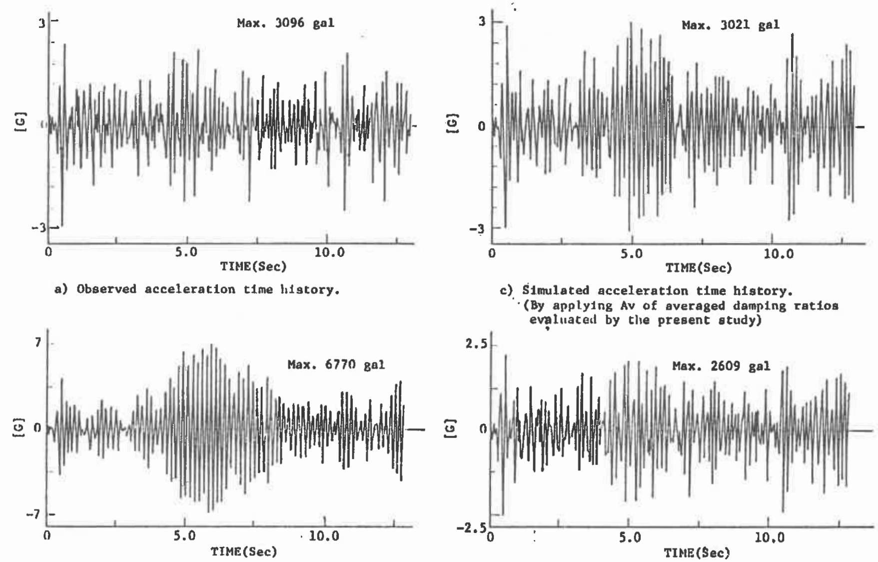


Figure 7. Estimated first vibrational mode for the mockup piping system.



a) Observed acceleration time history.

b) Simulated acceleration time history. (By applying 2% seismic damping of current Japanese design practice)

c) Simulated acceleration time history. (By applying Av of averaged damping ratios evaluated by the present study)

d) Simulated acceleration time history. (By applying Av+2Sd of damping ratios evaluated by the present study)

Figure 8. Comparison of simulated response acceleration time hitories for the mockup piping system with the observed response time history. Maximum input acceleration: 1250 gal.