AN EXPERIMENTAL STUDY ON THE RESPONSE OF A MODEL SYSTEM TO NATURAL EARTHQUAKES IN THE FIELD AND ON A SHAKING TABLE

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SUMMARY

This paper involves the details of the following experiments, that is, the observations of the responses of a three story building, equipment and piping models to natural earthquakes and those of the identical system on a shaking table. The authors compaired those results with several methods of response analysis which are generally used in the standard practice of earthquake resistance design of nuclear power plants.

Although the standard practice seemed to be established when the authors started their study, there were still several problems remaining in unsolved states. A set of these experiments was done to clarify the problems as follows:

(1) How much discrepancy is there between the result of theoretical response analysis and that of the field experiment to natural earthquakes?
(2) How do response factors fluctuate and is there any relation between response factors and the nature of earthquake patterns?
(3) Which is better: a floor response method or a composed machine-building response method for the analysis of machine-building systems?
(4) Which scheme to sum up the maximum responses of modes should be used, for example root of the sum of squares?
(5) How is a two-input model substituted for single input models in case of response analysis and how to sum up the responses of those models?

The series of the experiments had been done by the studying team of the Japan Electric Association under the sponsorship of the Agency of Science and Technology from 1968 to 1970. The authors studied and developed those problems as a working group for the analysis of machine-building systems. A three story building was built in Nagano City which is near to the area which became known by the famous Matsushiro Earthquakes Swam from 1965 to 1970. This building was planned to observe its response to the earthquakes from Matsushiro Area, and was equipped with a two-pipings-and-vessel system, a dual-springs-and-single-mass system and two two-degrees-of-freedom mass spring models. About sixty records had been obtained and analyzed, and those were compared with the results of the response analysis which was usually used in the design procedure. The results, the ratios of actual responses to theoretical ones were very much scattered. To check these mechanisms, the building was rebuilt on a shaking table and was reshaken by the records of corresponding ground shakings in Nagano.

The authors try to make clear the problems above mentioned in the view point of the design of nuclear power plants. And also they mention the existence of very large fluctuation of response factors caused by a stochastic nature of earthquakes besides the reasons which we can easily estimate.

1. Preface

One of the authors, Shibata has been engaged in developing the theory and the practice of the design of earthquake-resistant piping systems since 1960. A program for vibration analysis of piping systems, DYNAPS[1] was completed in 1964, and vibration tests of piping systems in a conventional steam power plant were done twice prior to developing the theoretical work. But no experiment on observing responses of piping systems to natural earthquakes had done until 1965. Once, Shibata and Akino planned to set instruments on the piping systems of JPDR (Japan Power Demonstration Reactor), but there was difficulty to pull out the signals through its containment vessel because of lack of available penetration channels. In 1965, a studying group of the Architectural Institute of Japan built three structures to observe their responses to natural earthquakes under the sponsorship of the Agency of Science and Technology. These buildings had indentical configurations, and they built on different types of soil conditions. One of them provided a piping system, L-shape, in its room. In some reasons, the results were very poor, but its maximum response factor was large, that is, approximately 20. And the importance of such a type of experiment was recognized.

At this moment the practical method of dynamic response analysis of piping systems was almost established, but there are still several problems to be remained unsolved for improving the way of response analysis. The authors had been studied on the multi-input response problem of a bridged piping system for several years since 1966. In this study their effort was mainly concentrated to establish a practical method for evaluating the response of a bridged piping system through a kind of modal analysis techniques. They did their study by using an analog computer and also checked theoretically. For their analysis, they employed one hundred pseudo-earthquakes and the records of several historical earthquakes, for example, El Centro, Taft and others. Through this study they recognized the importance of the fluctuation of responses of piping systems to earthquakes.

For the further study of their practice they joined the studying team of the Japan Electrical Association in 1968. For first two years they made the observation of the responses of a three story model building, in which several types of equipment and pipings were mounted, to natural earthquakes. That building was built in Nagano City which had been intended to be affected by Matsushiro Earthquake Swam (in Fig. 3). Almost 60 records were obtained and analyzed.

The amplification factors, especially of the response of the piping system, were scattered very widely, and most of them did not coincide with those obtained through simulations by an analog computer. Such a discrepancy between the observation and its simulation were considered to be caused by the lack of the initial parts of each ground motion record. So the authors started the new project of reshaking the identical three story model including equipment and pipings on an electro-hydraulic shaking table and analyzing the records of their responses to eliminate the effect of the lack of the part of input data.

In this short article, the authors want to summarize their two experiments on the response of a model piping system to natural earthquakes in Matsushiro and on the shaking table in Abiko, and to review their results.

2. Model

Models in Nagano City and that on a shaking table were almost identical. The model system consisted of a three story reinforced concrete building, and equipment and piping system as shown in Figs. 1, 2, 8 and 9. The building was a rahmen structure in the direction of NS or shaking, and a rigid structure in the other direction.

The schematic configuration of the model of equipment and pipings were as shown in Fig. 9. The piping system consisted of one cylindrical vessel and two Z shaped pipings. One was parallel to NS or the direction of shaking and the other was to EW or vertical to that. The following hangers and other supporting mechanisms were mounted on the pipings: vibration eliminators (VE), constant-force-type hangers (CH), wire-mesh-type damper (MD) and dash pots (OD), but thermal insulator did not cover the pipings. The models of equipment of this case were designed for checking the accuracy of the response analysis. A flat steel bar hanged on the ceiling of the third floor and penetrated its to the second floor, and the lower end was fixed at the second floor. A weight (M) was mounted on the flat bar as shown in Fig. 9. This model, a dual spring and single mass system is of a two input system. The model system in Nagano contained also two two-degree-of-freedom systems. This model consisted of leaf springs, box-shape masses and oil dash pots. Their vibration characteristics observed in Abiko are shown in Table 1. It can be said that their values coincide with the theoretical values.

3. Field Experiment in Nagano City

On some summer day in 1965, a seismograph in Matsushiro station of the Meteorological Agency suddenly observed many micro earthquakes. The number of earthquakes of everday had been increasing very steeply. It was the beginning of Matsushiro Earthquakes Swam. Since that day, August 3, 1965 and by July 15, 1968, that is, approximately for two years they had recorded 687,639 earthquakes, including 24 strong earthquakes of which scales were over VII of MM.

Many experimental works in seismology and earthquake engineering fields had been done for those several years by using this swam. A studying committee including some of authors was organized in the Japan Electric Association for studying the response of a structure, equipment and piping systems to those earthquakes. It was said that the main purpose of this field experiment was to check the practice of response analysis through modal analysis method. And that the responses of the structure, equipment and pipings to an actual earthquake should be compared with the analytical results of their responses to the records of underground or basement motion in each earthquake (see Fig. 10). A three story building was built in Nagano City near Matsushiro Area (Fig. 3). This building was equipped with a two-pipings-and-a-vessel system, a dual-spring-and-single mass model and two two-degrees-of-freedom models. Their schematic drawing (in Fig. 8) is the same as the other building which was built on a shaking table for reshaking, except the two-degrees-of-freedom models.

3.1 Results of Observation

About sixty records had been obtained over the period from January 1968 to March 1969. Their responses were checked by the simulation technique which was used as the usual dynamic analysis method in design procedure.

The amplification factors of the acceleration of the third floor to the basement had been scattered from 1.4 to 6.9 as shown in Fig. 4. Those of the equipment and piping systems were more scattered, for example, from 4.4 to 22.8 (out-of-plane motions of the piping A) as shown in Fig. 5. To make clear the cause of scattering of such amplification factors, an analog simulation for the responses of those systems to earthquakes was done. The study raised another problem, that is, the calculated values of responses are fairly lower than the observed ones. Even for the responses of a dual-spring-and-single-mass model (#2 in Fig. 8), the mean ratio of calculated values to the observed is 0.56 and their standard deviation is 0.33. The reason of such low figures of calculated values was estimated as the lack of the first phase of earthquake records used for the analog simulation due to the delay of the starter. In Fig. 6 one of the extreme cases is shown. In the first half second of actual record of response of piping high frequency waves were observed, however analytical acceleration response was very smooth. To the other type of earthquakes, sometimes the records agreed with the calculated curves very well as shown in Fig. 7. In this case the wave form of the input earthquake is a moderate wave and does not contain sharp high frequency components.

The studying group discussed the discrepancy of such figures of response factors, and they mentioned several reasons like the effects of non-linearity and so on. Also the corelation between the discrepancy of these figures and the magnitude or the distribution of epi-centres of earthquakes was checked. Finally they noticed that the shallow earthquakes near the site, that is, the epi-centres of those earthquakes belonged to Matsushiro earthquake area, caused more discrepancy. This means that the lack of the first phase, which contains sharp P-waves, of the input data used for the analysis has the large effect on amplification factors.

Therefore, they felt the necessity of a new project which the authors will report in next chapter, that is, checking of responses of the system to exact input waves both for the actual system and simulated system.

4. Measurement and Analysis of Response of Equipment and Piping Systems on a Shaking Table

4.1 Shaking Table and Input Waves

The table which they used is equipped in Abiko Division of the Central Research Institute of Electrical Power Industry, and is operated by Dr. Tsutsumi and his staffs of the earthquake resistant structure group of Civil Engineering Laboratory. Dr. Tsutsumi's group also had roles of constructing the building and doing the experiment on its response.

The maximum capacity of the shaking table is 120 ton and is shaken by hydraulic actuators, of which total vector force is 60 ton. As a input signal, displacement waves are used. Displacement waves are obtained by the attached hybrid computer by integrating acceleration waves which we usually use. This time, they employed twenty local earthquakes which observed at Nagano site with the responses to them. They also used El Centro and Taft earthquakes. The accuracy of the acceleration on the table was kept to be as high as possible, but the authors could not satisfy completely. For checking the reproducibility of the wave form and the response, the authors tried to shake the model by the identical earthquakes in ten times.

Comparisons of the responses obtained on the shaking table with analysis and simultation can be made in several ways as shown in Fig. 10. The comparisons through the routes A and B are important in engineering sense, and here the authors made comparisons through A, that is, to the results obtained by the floor-response technique.

4.2 Fluctuation of Response to the Identical Earthquakes

Some fluctuation of the responses to the ten identical earthquakes caused by the non-linearity of the system was expected, but the result was greater than the authors had been expecting. Figure 11, shows the wave forms of the responses. The differences between each earthquake waves are not significant, but those between the responses are very large. As shown in Fig. 11, the effects on higher modes are strong. The patterns of the distribution of the maximum accelerations on the piping system are shown in Fig. 12. The dispersion factors, that is, the ratio of standard deviation to the mean, have the very significant values to the piping system as shown in Table 2. The value of the building was only 1%, but that of the piping systems was 9%.

4.3 Histograms of Response Factors

In Fig. 13, the examples of histograms of response factors ---- amplification factors in each condition. Their tendencies are quite similar to those of the Nagano Cases, that is, the response factors in each condition are scattered very widely. That to El Centro earthquake sits near to average, and that to Taft earthquake shifts to higher side little bit in most cases. These data can be summarized into statistical form as shown in Table 3. The dispersion factors are large and have a tendency to depend heavily on the damping values. It can be understood that the slight differences between each resonance condition affected more strongly on their response factors in the case of lower damping. And the lack of the initial phase made the response curves of the both, on the shaking table and by the simulation through the analog computer, smoother than that to actual earthquakes, and also made coincide each other better. So we can say that the disagreement of the response factors between the actual observed values and the analytical ones mainly came from the lack of the initial portion of the ground motion records.

5. Scheme of Summing up Responses of Each Mode

In case of the response analysis of a bridged piping system, it is convenient, if we can obtained it through the ordinary floor response technique. Shimizu and Shibata made one approach(2) to obtain the response of a bridged system to multi-inputs.

By assuming that the input motions to the bridged system at both points are independent to each other, the response could be described by an equation theoretically. From the equation, Scheme A of eqs. (1) will be obtained. In Fig. 14, a set of the examples of response curves of the actual system and the analog simulation. In the case of Fig. 14, they agreed with each other very well.

The authors introduce the following five schemes to sum up the results of modal analyses of each mode in the case of the out-of-plane vibration of the piping system.

$$\begin{aligned}
\text{Scheme A} &= \sqrt{\sum_j \sum_r (x_{rj}^2 + y_{rj}^2)} \\
\text{Scheme B} &= \sum_j \sum_r \sqrt{x_{rj}^2 + y_{rj}^2} \\
\text{Scheme C} &= \sqrt{\sum_j [(\sum_r x_{rj})^2 + (\sum_r y_{rj})^2]} \\
\text{Scheme D} &= \sum_j \sum_r (|x_{rj}| + |y_{rj}|) \\
\text{Scheme E} &= \sqrt{\sum_r [(\sum_j x_{rj})^2 + (\sum_j y_{rj})^2]}
\end{aligned} \qquad (1)$$

where x_{rj} is the maximum response of the j th mode horizontal motion to a supporting point r and y_{rj} is the maximum response of the j th mode vertical motion to a supporting point Scheme A is understood as "the root of sum of squares" and is obtained from a theoretical result directly. In the case described here, the supporting points 1 and 2 were on the first floor and the third floor of the building respectively, so the inputs to the piping system are correlated rather strongly in each mode. The phase relations between two inputs are determined by the relation of the eigen-frequencies of the piping systems to those of the building. If the first mode of the piping systems resonates to the first mode of the building, then x_{11} and x_{21} should be added, but if resonates to the second mode of the building, then $(x_{11} - x_{21})$ should be employed. But practically the authors applied this idea to Scheme C to avoid the difficulty to consider the phase relations and put the relation on a safety side or over-estimate it. Scheme D is called "the sum of absolute values" and expected to give its upper-limit.

In Fig. 15 some results, the ratios of the actual data to analytical values, are shown. Here, the authors used Runge-Kutta-Merson Method to integrate equations. For a dual-spring-and-single-mass system the analytical values are smaller than the actual values in general. For the piping system the results seem to be reasonable. Cases like the former example arise sometimes. The authors judge that they were caused by overestimating the damping co-efficient of the system. They considered such an overestimation mainly comes from the flow of vibration energy in the whole system(3).

As a conclusion the authors judge that Scheme C is reasonable, but Scheme D, absolute sum, is too conservative. But also, we should pay our attention to the fact that the dispersion factors of every schemes are large and the same order.

6. Acknowledgement

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Reference

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2) Shimizu, N. and Shibata, H. : J. of Institute of Industrial Science (Univ. of Tokyo), Vol. 21, No. 6 (June, 1969) p. 405.

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(Hz),(%)

Model	Structure	Pipings		Dual Spring and a Mass System
		Outof-plane (A)	In-plan (B)	
1st	(5.7) (1.8)	3.12 (3.26) (0.186)	5.34 (5.27) (0.076)	(3.79) (0.108)
2nd	(20.5) (1.5)	6.75 (6.97) (0.121)	14.92 (14.87) (0.091)	(11.70) (0.070)
3rd	(33.1) (1.3)	16.18 (16.3) (0.089)	21.67 (20.37) (0.174)	(22.06) (0.057)

Frequency, calculated by DYNAPS, (Freqency, observed), (critical damping ratio)

Table 1. Vibrational Characteristics of Structure, Pipings and Equipment

Position	Average Acc. (gal)	Dispersion Factor
Roof Floor (RF)	113.9	0.01
Lower Supporting Point of Piping	71.7	0.01
OD point of Piping (pt. C)	229	0.09

Table 2. Average Response Accelerations and Their Dispersion Factors to Ten Repetitions of an Identical Earthquake

	Condition of Appendage	Critical Damping Ratio %	Response Factor	
			Average	Disp. Factor
Dual Spring and a Mass System	+ Mass (9 kg)	0.1	9.79	0.51
	+ Mass (9 kg) + OD	8	2.91	0.31
	+ Mass (44 kg)	0.1	4.94	0.46
	+ Mass (44 kg) + OD	6	2.07	0.41
Piping Outof-plane (A)	NA	0.2	6.32	0.38
	+ CH	3.3	3.01	0.34
	+ OD	25	1.50	0.16
	+ CH + OD	17	1.39	0.19

Table 3. Fluctuation of Response Factors of Pipings and Equipment

Fig.1. Outside View of the Model Building in Nagano Site

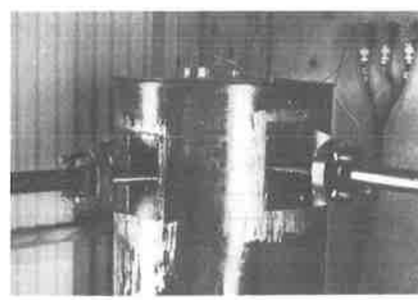

Fig.2. A Part of a Vessel and Piping Model

Fig.3. Map of Nagano Site

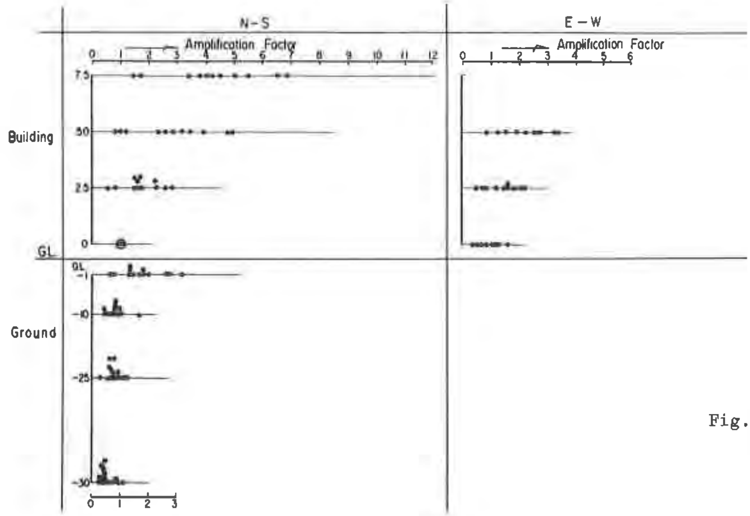

Fig.4. Distribution of Amplification Factors of Model Building and Ground in Nagano Site

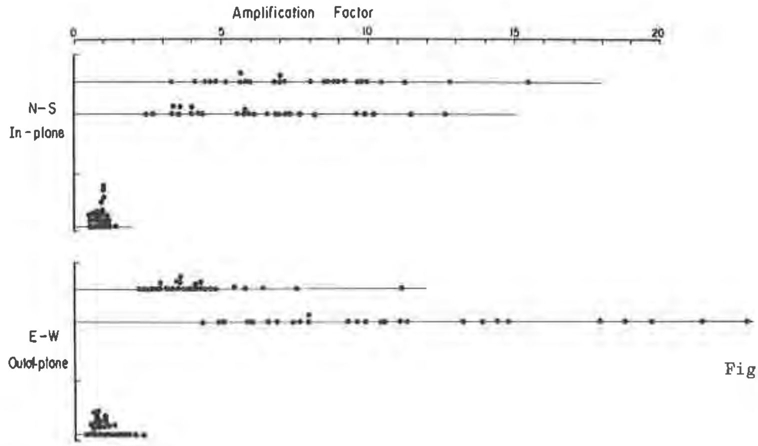

Fig.5. Distribution of Amplification Factors of Pipings in Nagano Site

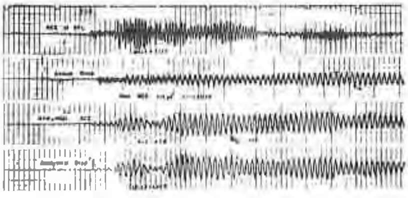

Fig.6. Comparison of Actual Response to Analytical Result; Out-of-Plane Vibration of Pipings

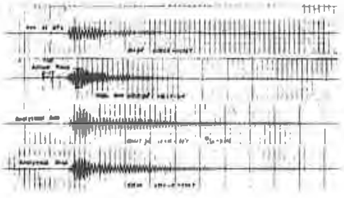

Fig.7. Comparison of Actual Response to Analytical Result; In-Plane Vibration of Pipings

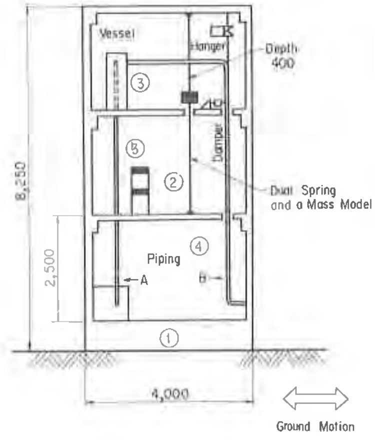

Fig.8. Schematic Drawing of the Model Building

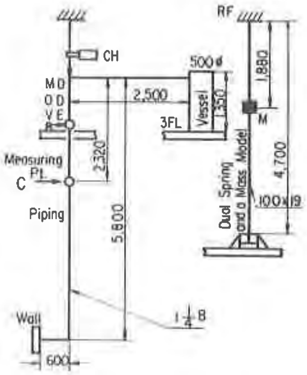

Fig.9. Schematic Drawings of Pipings and Equipment

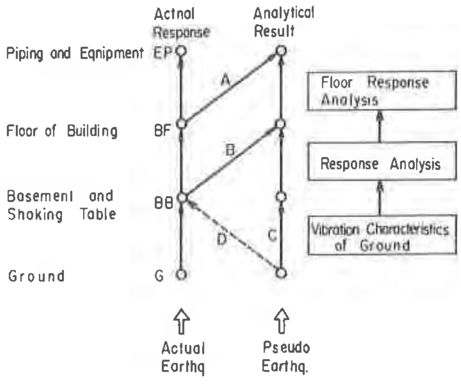

Fig.10. Schematic Diagram of Response Analysis

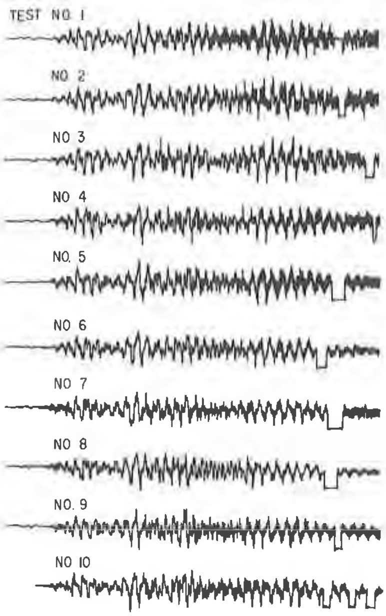

Fig.11. Responses of Piping on Shaking Table to Ten Earthquakes Generated by an Identical Input Wave

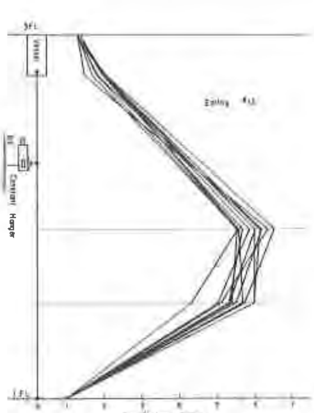

Fig.12. Distribution of Maximum Acceleration of Piping to Ten Identical Earthquakes

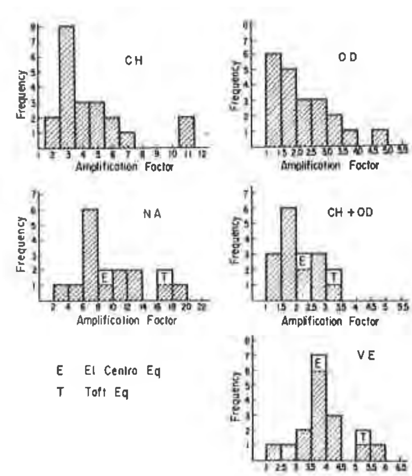

Fig.13. Histograms of Amplification Factors of Pipings

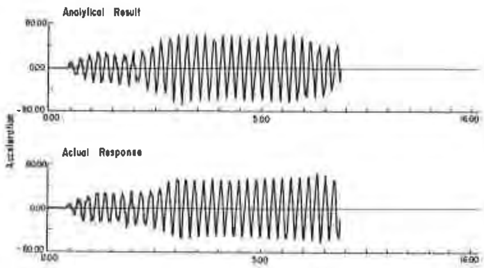

Fig.14. An Example of the Response of Pipings; Simulated Response and Actual Response

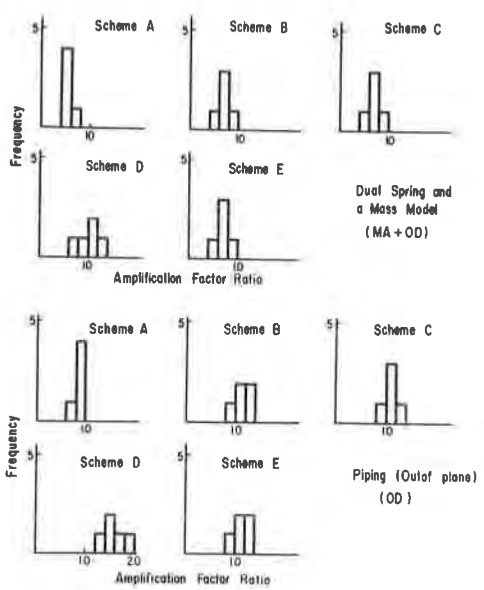

Fig.15. Histograms of the Ratios of Simulated Response to Actual Response of Pipings and Equipment