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ON EXPERIMENTAL EVALUATION OF RESPONSE REDUCTION EFFECT OF PIPING SYSTEMS DUE TO GAP AND FRICTION

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SUMMARY

In this paper, an experimental study on the seismic response of piping systems. By vibration tests with the actual-size piping-supporting structure model, we particularly evaluate the effect of the gap and friction which can be generally observed among the piping and supporting structures in various kind of facilities. After summarizing the experimental results under various vibration conditions, we estimate a " response reduction factor " from which the response properties of the piping system can be conventionally calculated.

INTRODUCTION

Piping systems are generally supported at multiple points of several supporting structures in petro-chemical plants. For example, various support types, such as the guide-type support and resting-type support as shown in Fig. 1, are utilized for supporting the weight of piping and increasing its stiffness. Therefore, in seismic conditions, the piping systems should be subjected to multiple support excitations through the above supporting structures. The response analysis problem in such a situation should be treated as a multiple excitation one.1)

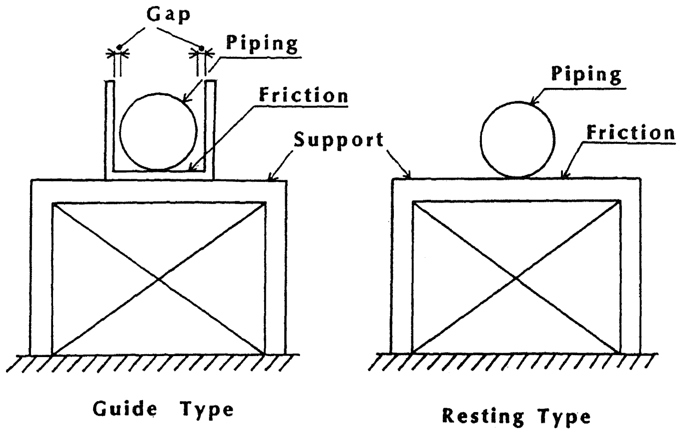

Fig. 1 Schematic Drawing of Supporting Structures

On the other hand, a clearance which is given as an allowance for thermal expansion or a gap which happens during construction and friction among the pipe and the supports have considerable effects on the seismic response of the piping system.2), 3) Several investigations concerning the dynamic response characteristics of piping-supporting systems which depend on these nonlinear effects have been made for nuclear power plants, but those for common petrochemical plants have been lacking. In particular, there have been only a few reports on nonlinear response problem, such as the experimental evaluation of response effects due to these nonlinearities.

Thus, from the point of view of rationalizing the aseismic design of piping systems, it becomes very important to establish a conventional calculation method considering both the multiple excitation problem and the nonlinear response problem in their dynamic response analysis. In this paper, first, an experimental investigation using a full-sized, piping-supporting structural model is carried out on a large-scale shaking table. The characteristics of the nonlinear response behavior of this piping model are particularly investigated. Based on the experimental results, the nonlinear response properties are numerically evaluated in order to apply to the aseismic design of piping systems. The response reduction effects due these nonlinearities obtained through the vibration test are represented in terms of a " response reduction factor ". Based on the equivalent modal parameters for nonlinear piping-support systems obtained by using an equivalent linearization technique 4), the characteristics of the response reduction factor are also investigated. Finally, these experimental results are clarified by numerical simulation with a simple model.

VIBRATION TESTS WITH ACTUAL PIPING-SUPPORTING MODEL

The piping-supporting model introduced for vibration tests is a straight pipe 6 m long as shown in Fig. 2. The diameter and thickness of the piping are 3/ 4" B(ϕ27.2 mm) and Sch 40 (2.9 mm), respectively; and its material selected is STPG-38. This model corresponds to a part of the small inside diameter piping which is commonly utilized in the petro-chemical engineering plants. In order to simulate the multiple excitation conditions, a 5 % difference in the natural frequency values between two supports is given by installing additional weights on one of the supports. The results obtained by vibration tests using this piping-supporting model are compared with those from the piping model with two supports having an identical natural frequency. In this paper, the former model with two different supports producing multiple support excitations is termed "multiple excitation" or "asymmetrical case", which is abbreviated to "Asym.". The latter model subjected

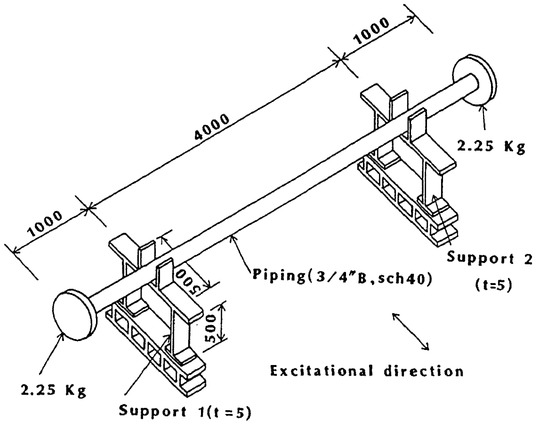

Fig. 2 View of Test Apparatus

to uniform excitations due to two identical supports is termed "uniform excitation" or "symmetrical case", which is abbreviated to "Sym.". Each stopper installed for restraining the piping behaviour is set up on one of the supports; hence for total gap size on both sides of the pipe, two values of 0.5 mm and 1.05mm are used. These values can be briefly recognized as an actual measurement. On the other hand, the frictional effect is realized by the sliding pads (SUS-SUS) installed at both supporting structural models. The coefficients of static friction measured by static loading tests are about 0.2 through 0.5. These value are almost equivalent to that in the actual structure situation.

Two different piping-supporting models are tested under the following three support conditions;
(1) linear support condition without gap and friction
(2) nonlinear support condition with only gap
(3) nonlinear support condition with both gap and friction
Pseudo-random waves are mainly used for the vibration test. The input acceleration of the shaking table, the acceleration responses at mid-point of the test pipe and of two supports, and their relative displacement responses to the shaking table are measured and automatically recorded by a digital computer system.

TEST RESULTS AND EVALUATION OF RESPONSE REDUCTION EFFECT

For two different piping-supporting models, the measured maximum displacement at mid-point of pipe relative to the shaking table through the vibration test are shown in Fig. 3. For an example of the multiple excitation case, the maximum relative displacement responses just under the gap-condition and also gap-friction condition at an input level of 200 cm/s^2 are reduced; about 66 % and 60 % from that under linear condition, respectively. From this figure, it can be shown that the nonlinearities due only to gap, and both gap and friction have dominant reduction effect on the relative displacement response.

Next, we numerically evaluate the response reduction effect and examine its reduction characteristics. By comparison of the testing results under nonlinear - gap and friction- conditions with those under linear condition, we can represent the response reduction effect due to gap and friction as

$$x_n(\max) = (1-\beta)\ x_l(\max) \tag{1}$$

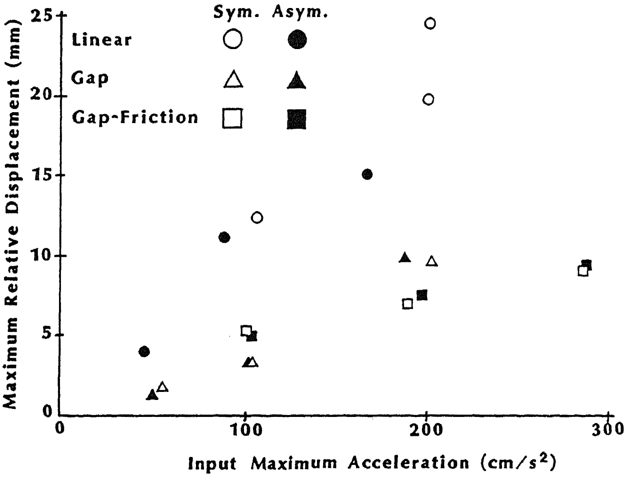

Fig. 3 Comparison of Maximum Relative Displacement Responses

This relation means that the maximum nonlinear displacement response x_n(max) can be conventionally calculated in terms of the linear maximum response x_l and response reduction factor β. The comparisons of response reduction factors are shown in Figs. 4 and 5. Figures 4 and 5 correspond to the multiple excitation case and uniform excitation case, respectively. In these figure, the values of input level on the abscissa are normalized by the input level at which piping has continuous collision with both stoppers. The solid curve shows the calulated reduction factors based on Eq.(1) using the results obtained from the vibration tests having gap and friction, and the dashed curve does those having only gap. And, another curve shows the reduction factors due only to friction obtained by above two reduction factors under the assumption that effects due to gap and due to friciton are independent with each other.

Also, the reduction factors denoted by the symbol of ○ in these figures are calculated by the following approximate equation constructed by assuming the input motion to be a white-noise motion 5) and the first mode of piping to be dominant, using the linear modal parameters and the equivalent modal parameters under the condition with both gap and friction.

$$\frac{1}{\zeta n\ \omega n^3} = (1-\beta)\ \frac{1}{\zeta_l\ \omega_l{}^3} \tag{2}$$

where ω_l and ζ_l correspond to the natural circular frequency and the damping ratio of the first mode of a linear system without gap and friction, respectively, while ωn and ζ_n correspond to the equivalent natural circular frequency and the damping ratio of the nonlinear system, respectively.

All reduction factors grow large as the nondimensional input level increases. From an example of multiple excitation case, the values of response reduction factor β due only to gap, due only to friction and due to both gap and friction at an input level of 8 become about 0.30, 0.60 and 0.65, respectively. From these figures, it can be especially shown that the response reduction effect due to friciton is dominant compared with that due to gap in the nonlinear response of piping-supporting systems under the support condition with both gap and friction. Furthermore, from Fig. 5, it can be clear that the response reduction effect depends on the gap size; in other words, the larger the gap size grows, the stronger the response reduction effect due to gap and friciton becomes. On the other hand, the reduction factor obtained through Eq.(2) almost agrees with the solid curves for the multiple excitation case and uniform excitation case. Therefore, if the effective linearization method can be utilized, this reduction

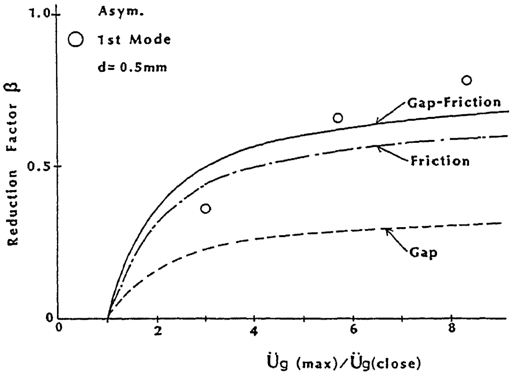

Fig. 4 Comparison of Reduction Factors (In Multiple Excitation Case)

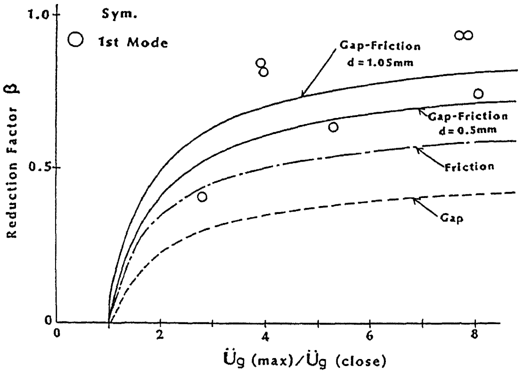

Fig. 5 Comparison of Reduction Factors (In Uniform Excitation Case)

factor using the equivalent dynamic characteristics of a piping-supporting system should become of a practical use. Thus, the proposed response reduction factor β is expected to be utilized for a practical application for nonlinear response analysis of general piping systems in petro-chemical plants.

NUMERICAL SIMULATION WITH SIMPLE PIPING-SUPPORTING MODEL

By numerical simulation with a simplified model, the reduction effect due only to gap on the maximum displacement response of piping is evaluated in terms of response reduction factor β. Figure 6 shows a two degree of freedom piping-supporting model for numerical simulation and for the supporting structure as shown in Fig. 1. This model with only gap-effect corresponding to a guide-type support represents a fundamental mode of vibration, whereby piping response have a significant influence on the supporting structure, and a fundamental mode of vibration in response of support itself. Masses of piping and support are m_p and m_s, respectively, and their related spring constants and damping coefficients are k_p, k_s, c_p and c_s. In this model, a well known typical bilinear model showing the relation of restoring force f_g due to spring constant k_g and displacement x_n of piping relative to the support is introduced.

Figure 7 shows a comparison among the maximum relative displacement responses of nonlinear model with gap, linear model with infinite gap size and linear model with zero gap size using white-noise input excitations. This is for the case of mass ratio, $m_p/(m_p+m_s)$, $\lambda = 0.5$, ratio of natural frequencies of piping and support, $\alpha = 1.0$ and ratio of spring constants, $(k_p+k_g)/k_p$, $b = 10$ which are utilized in the practical design of piping systems. In this figure, the solid curve denotes the nolinear maximum response $x_n(\max)$, upper dashed line does the linear maximum response $x_l(\max)$ obtained by assuming that piping has no collision with supporting stoppers; namely infinite gap size, and lower line does the linear maximum response $x_o(\max)$ obtained by assuming that piping is fixed by the both stoppers and is vibrated together with them; namely zero gap size. Also, in this figure, the maximum displacement is normalized by that due to input level at which piping has continuous collision with both stoppers and the input level A is treated in a same manner. From this figure, it can be shown the maximum nonlinear response almost increases in proportion to the value of input level and the rate of its increase approximately equals to that of maximum response of linear model with zero gap size. This means that the collision of piping with both stoppers becomes vigorous as the input level increases; that is a state of apparently closed gap, and then the response characteristics of nonlinear model are almost similar to those of linear model with zero gap size.

Using the simulation results, the response reduction factor calculated by Eq.(1) is shown in Fig. 8. This is for an example of mass ratio $\lambda = 0.5$, ratio of spring constants $b = 2$ and several values of ratio of natural frequencies α. According to the value of α, the response reduction factors show some variations.

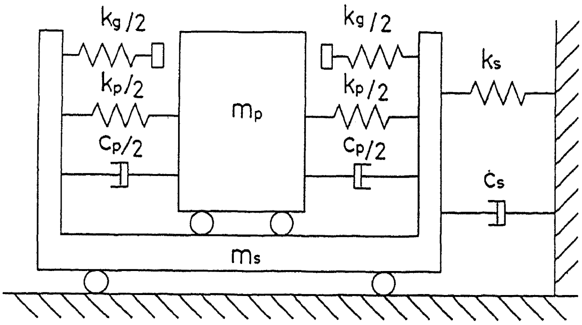

Fig. 6 Piping-Supporting Model with Gap-Effect

From this figure, however, it can be clear that their characteristics due to the input level are almost similar to that obtained from the experimental results. Furthermore, at the input level of 8, the value of reduction factor becomes approximately 0.30 as described in the previous chapter.

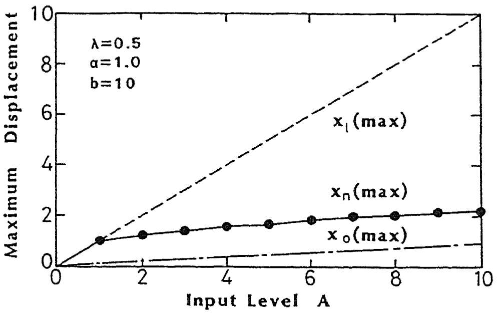

Fig. 7 Comparison of Maximum Relative Displacement Responses

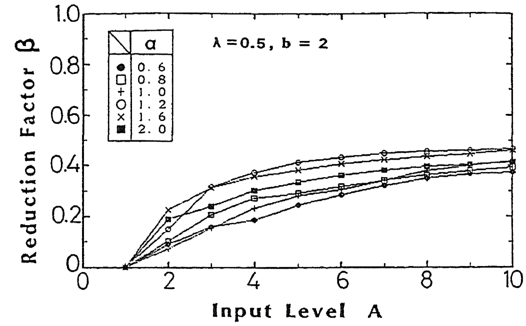

Fig.8 Characteristics of Response Reduction Factor

CONCLUSIONS AND ACKNOWLEDGMENT

Both vibration tests with an actual piping-supporting model having gap and friction and numerical simulation with its simpified model are carried out by using pseudo-random waves. The response reduction effect due to these nonlinearities is evaluated and discussed. The main results are summarized as follows.

(1) Nonlinearities due only to gap and to both gap and friction have significant reduction effects on the relative displacement responses of piping systems for both multiple excitation case and uniform excitation case.

(2) As for the results of the response reduction effect numerically evaluated in terms of the reduction factor β, the reduction effect due to friction becomes dominant in the case where both gap and friction exist.

(3) The reduction factor considering the dynamic characteristics of an equivalent modal parameters almost agree with the results obtained through vibration tests.

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