SMiRT-12 / K. Kussmaul (Editor)

K19/1

A SEISMIC RESPONSE TEST OF PIPING SYSTEM WITH LIQUID COUPLING

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Abstract

In order to estimate effects of internal liquid column on piping seismic response, a vibration test has been conducted. Test results has shown that valve open/close operations changed liquid boundary condition and caused remarkable change in seismic response of pipe and liquid. This coupling effects agreed with analysis considering liquid wave propagation and valve conditions. The test and analysis have also shown that traditional method using lumped mass model of liquid could predict only seismic respose without dynamic liquid coupling.

1 INTRODUCTION

Dynamic coupling between pipe and internal liquid has been studied for many years. Some theoretical studies have been presented on coupled seismic response of piping system [1,2,3,4,6]. However, large scale vibration tests are required in order to validate analytical methods. The authors have conducted some experiments on seismic response of piping system with liquid coupling [4,5]. Liquid systems in real piping are under various boundary conditions due to operational requirement. Then, the effects of liquid coupling in various valve conditions should be investigated. Thus, the authors have conducted a vibration test of liquid-filled piping which includes a pump and valves to simulate practical boundary conditions of liquid.

2 TEST MODEL

2.1 A Piping Model and Test Method

A test model consists of a piping, a pump and three valves. A vessel is used for water supply and liquid boundary, but not on the shaking table. Figure 1 shows a layout of test model on the shaking table. Main specifications are shown in Table 1.

Measurement sensors are located as shown in Fig.1. Two cases of valve A condition, open or close, have been tested in order to compare the different boundary effects of liquid, one is close-open boundary for main liquid column (from closed valve A to tank return nozzle) and the other is open-open (liquid column from tank supply to return). The pump is not operated, then water is rested in the whole system. Test cases are shown in Table 2.

2.2 Basic Characteristics of Test Piping Model

Natural frequencies are obtained by experiment and calculation as shown in Table 3.

In this eigen value analysis, water is simply treated as added mass to pipe. Figure 2 shows measured vibration modes. Natural frequencies of main liquid column are shown in Table 4. The measured pressure wave propagation velocity was about 1180m/s in case of all three valves closed condition. But this value did not agree with the resonance tests in which the pump inner water is included into the liquid column. Thus the post-test corrected values were estimated by comparing with analysis.

3 COUPLED RESPONSE BY SINUSOIDAL EXCITATION

The lowest structural eigen frequency of test model is near to the 1st liquid column resonance frequency, and therefore, coupling response is predicted to occur near 1st natural mode of the system. An conventional added mass model of liquid gives only one resonance frequency at 6.3 Hz under 10 Hz from eigen value analysis. But, the test results clearly showed two distinguished resonance frequencies. The observed coupling response were different in two valve conditions. This coupling phenomena can be simulated by the two-mass model as shown later.

3.1 Coupled Response in Valve Condition No.1

Figure 3(left) shows the comparison of sinusoidal response curves obtained from experiment and calculation by simple analogical two mass model in valve condition No.1. The experimental results show two resonance frequencies at 5.4Hz and 7.3Hz. These are different from the value 6.3Hz by lumped mass model. The results from the parameter-adjusted analogical model approximately agree with those of experiment. Thus, these two resonances are explained to have occured as a result of coupling between sturctural vibration of resonance 6.3Hz and liquid column vibration of resonance 5.7Hz.

Measured pressure and acceleration responses at each coupled resonance frequency are plotted along pipe configuration in Fig.3(right), in which pressure response is shown in a form of physical liquid force to pipe. The figure clearly shows the different phase relations between acceleration and pressure at two resonance frequencies. Liquid forces at both ends of the main straight part (marked by ↙) are in opposite direction, namely same phase in pressure. Therefore, the liquid force is produced by the response of the whole liquid column, not the pipe's local vibration.

3.2 Coupled Response in Valve Condition No.2

In this case only one peak frequency 6.3 Hz was measured under 10 Hz, and two weak resonances at 10.1 Hz and 12.6 Hz were observed as shown in Fig.4. The former is the liquid 1st eigen mode for open-open boundary condition and the latter is the 2nd mode of structural response. In this case, excitation effect on liquid is very small because of fully opened valves at both end, and thus, liquid response is lower than the case No.1. Coupling effect is very weak in this case.

In this case, pressure response at 6.3 Hz is not related to liquid column resonance but to forced movement of liquid by pipe local vibration. Liquid force to the main straight part is in same direction at both ends. Namely, pressure at both ends are in opposite phase.

This result explains that pressure variation have been locally produced by pipe's 1st mode vibration.

4 COUPLED RESPONSE BY EARTHQUAKE WAVE EXCITATION

4.1 Result of Experiment

A similar results have been observed in earthquake wave excitation tests. Figure 5 shows shaking teble accelerations and pipe pressure and acceleration responses. No.1 valve condition gives the higher response than No.2. Acceleration at measuring point A8X of case No.1 is about two times larger than that of case No.2. This is due to the 2nd coupled frequency(7.3Hz) of case No.1 is more close to the main peak of the excitation spectra.

4.2 Comparison with Time History Analysis

A coupled seismic response calculation method[4], which uses modal analysis for structural response and characteristics method for liquid response, is used to evaluate the difference of piping response in each valve condition. This method involves axial liquid force to pipe and pipe wall boundary to liquid pressure wave propagation. Valve opening or closing conditions are also taken into account. Fluid friction is neglected, and pressure wave velocity $a = 940$m/s in Table 5 is used. Structural parameters are same in two valve conditions.

Figure 5 shows the comparison between responses of experiment and calculation for each test case. There is a fairly good agreement between vibration test and analysis. As previously described, the case No.2 shows very little coupling between liquid and pipe. In such case, liquid can be treated by lumped mass. Trial calculations by a lumped mass model have shown almost same response waves as those in Fig.5(ritht). But the coupled response of Fig.5(left) can not be simulated by traditional lumped mass methods.

5 CONCLUSION

Typical cases are described in this paper, but other valve conditions have shown different seismic response in same vibration test. Based on the test and analysis, it was shown that this coupling effect was well simulated by the authors' analytical method, but traditional lumped mass methods could simulate seismic response of only the case without coupling between pipe and internal liquid. These results show that such liquid coupling is an important factor to predict the exact seismic response of piping systems with many valve operations and liquid conditions.

REFERENCES

[1] F. J. Hatfield and D. C. Wiggert: "Response of Pipelines to Seismic Motion in the Axial Direction", PVP-Vol.127, ASME(1987), pp.289-295.

[2] F. Hara: "Seismic Vibration Analysis of Fluid-Structure Interaction in LMFBR Piping Systems, J. of Pressure Vessel Technology, Vol.110, ASME(1988), pp177-181.

[3] F. J. Hatfield and D. C. Wiggert: "Seismic Time-Response of Liquid-Filled Piping", PVP-Vol.140, ASME(1988), pp1-6.

[4] Ogawa, N. and others: "Coupled Seismic Response of A Piping and Internal Pressurized Liquid ," PVP-Vol.157, ASME(1989), pp191-196.

[5] Ogawa, N. and Minowa, C.: "A Seismec Response Test of Piping Sysstem Under Conderation of Liquid Coupling and Valve Conditions", PVP-Vol.232, ASME(1992), pp61-68.

[6] R. A. Uras, W. K. Liu, D. C. Ma, and Y. W. Chang: "FSI Analysis of Piping Systems Under Seismic Excitation", PVP-Vol.223, ASME(1991), pp25-28.

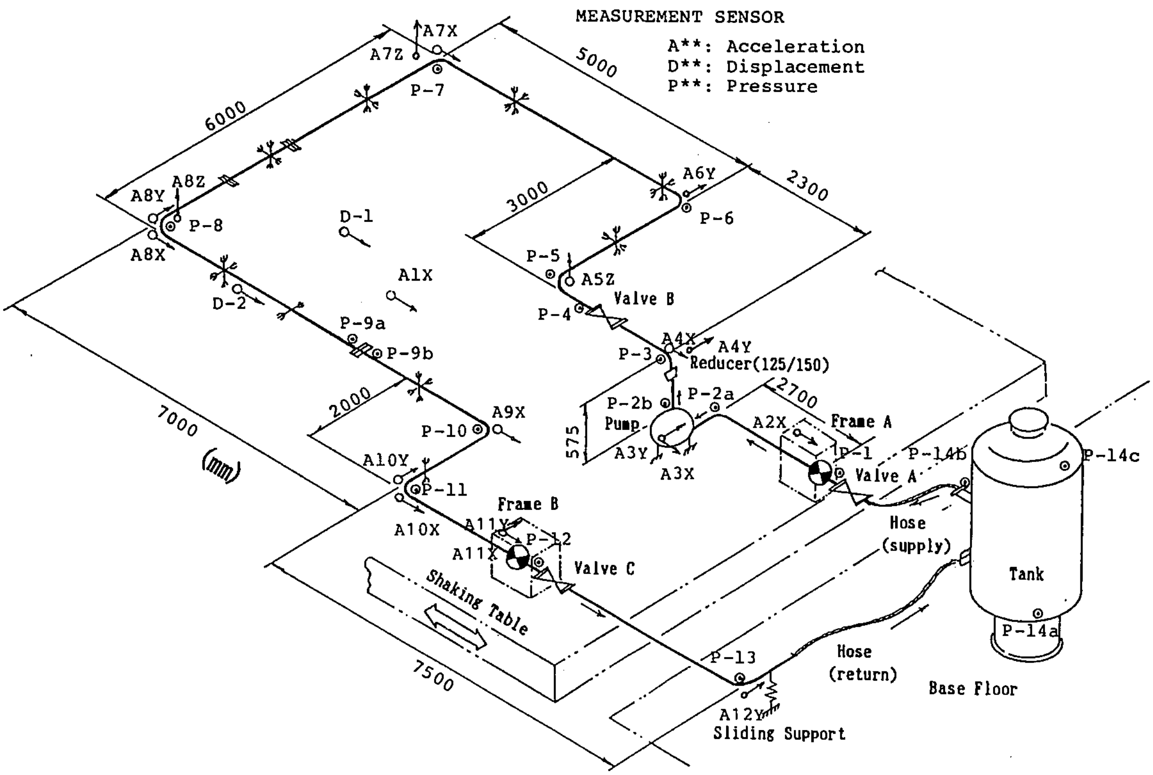


Fig. 1 Test piping system and location of measurement sensors

Table 1 Details of the test system

Item	Dimension, Capacity etc.
Pipe	D=150 mm, t= 5 mm Total length : 46 m Pipe support : Rod restraint, Frame anchor 100% water-filled and pressurized (400 kPa)
Pump	Centrifugal pump, 45 kWH (no operation in described cases)
Valve	Pump suction side (A, close or open) Delivery side (B, always open) Return to Tank (C, always open)
Tank	10ton, outside of the shaking table 90% filled water with free surface Closed and pressurized (400 kPa) Flexible hose connected to suction side(5.5 m) and return side(2.4 m)

Table 2 Test case

Case	Valve condition (B, C: open)
No. 1	Valve A: Close
No. 2	Valve A: Open

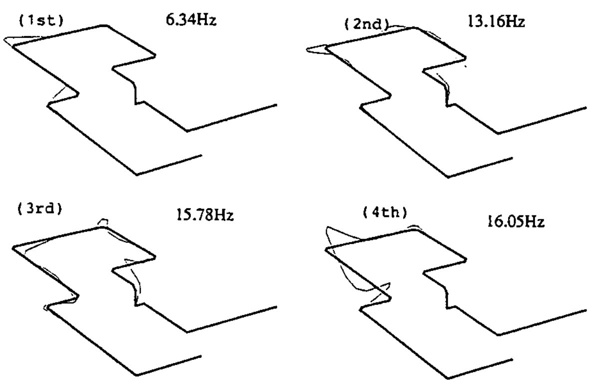


Fig. 2 Structural vibration mode by measurement
(Valve condition No. 2)

Table 3 Structural vibration chatacteristics in liquid-filled condition

	Natural Frequency (Hz) Prediction	Natural Frequency (Hz) Measured*	Damping Ratio Measured*
1	6.3	6.3	0.02
2	13.2	12.7	0.015
3	15.8	15.6	0.013
4	16.1	16.2	0.009

*Measured in case of valve condition No.2 (Case of very weak coupling)

Table 4 Liquid column resonance frequency in each valve condition

Valve condition No.	Liquid length L (m)	Resonance frequency (Hz)
1	41.0	5.7 (α= 940m/s *)
2	46.5	10.1 (α= 940m/s *)

* Pressure wave propagation velocity α is post-test estimated value.

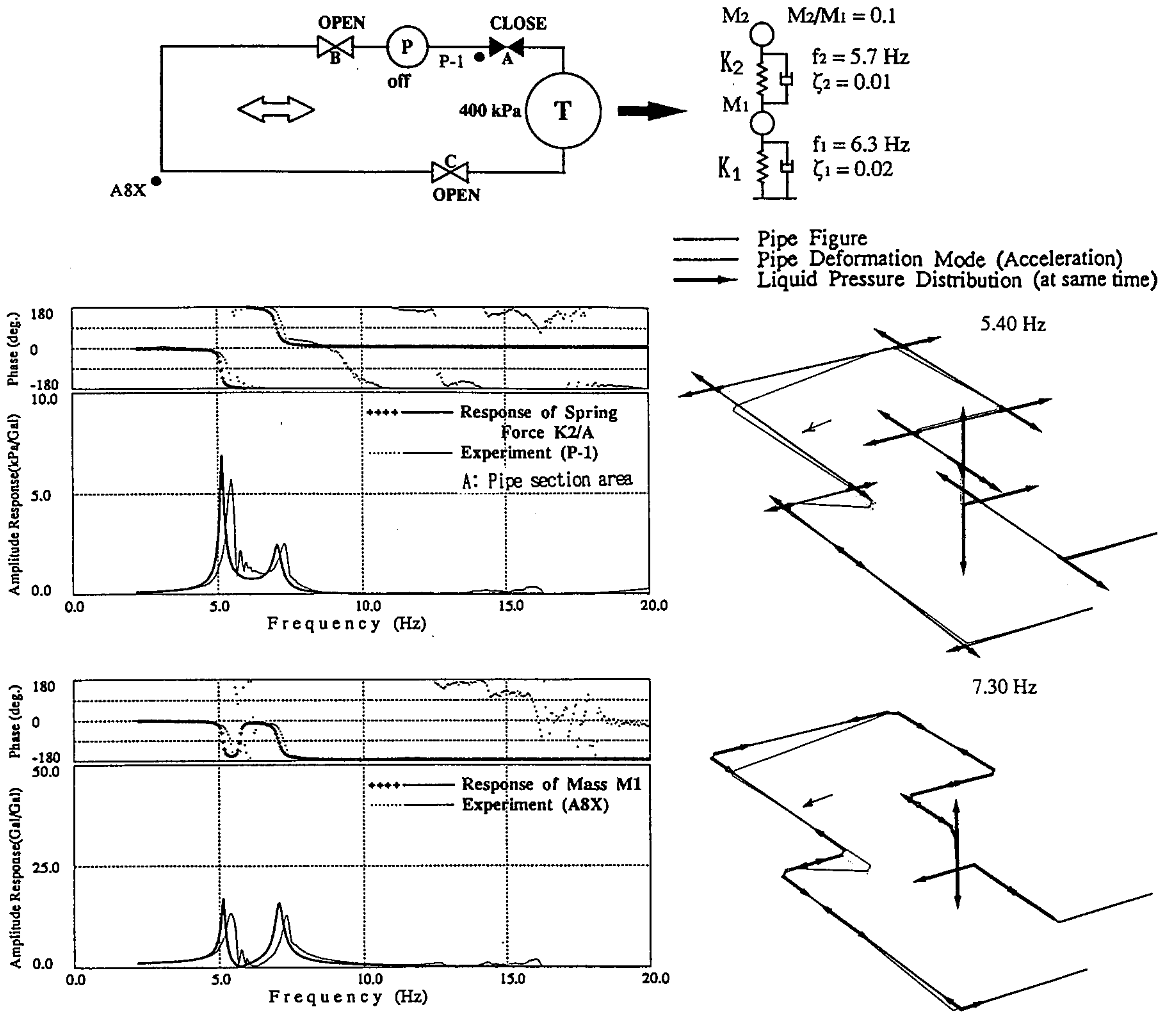


Fig.3 Left : Response curves by experiment and simple two mass model calculation
Right : Measured vibration mode of pressure and acceleration at coupled resonances (Valve condition No.1, case of strong coupling)

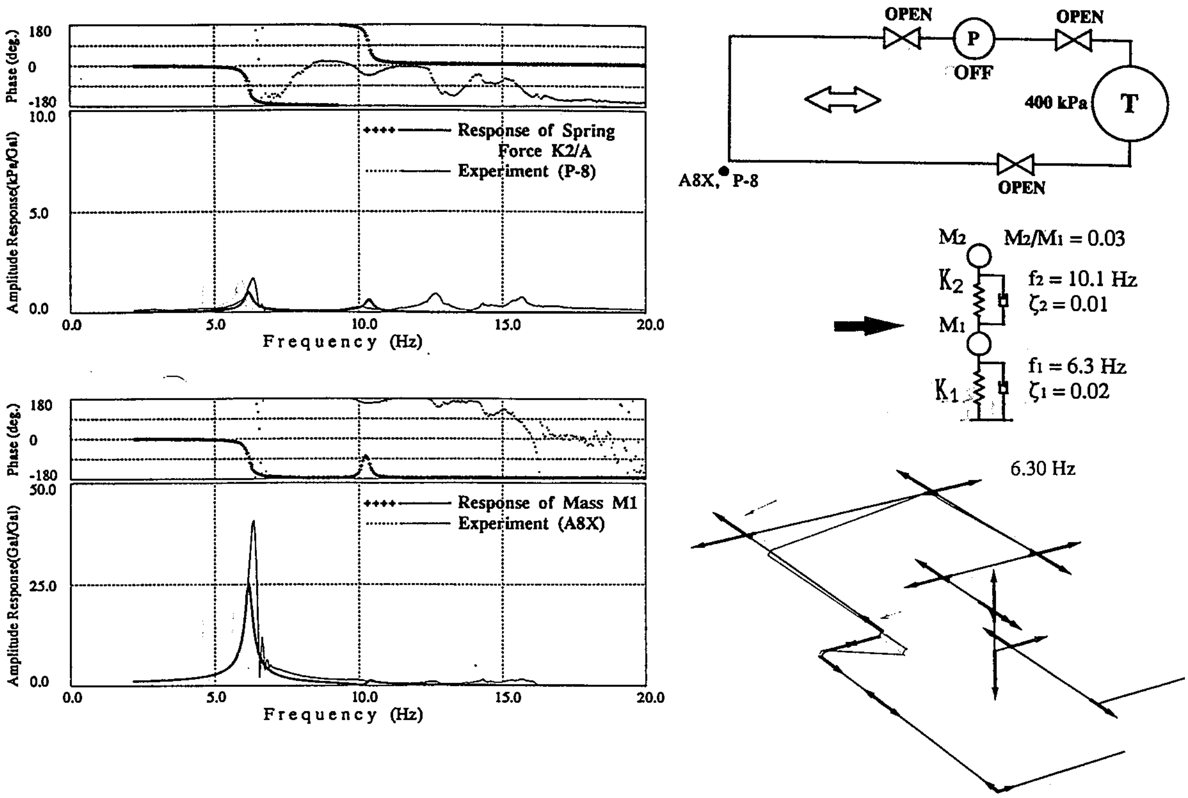
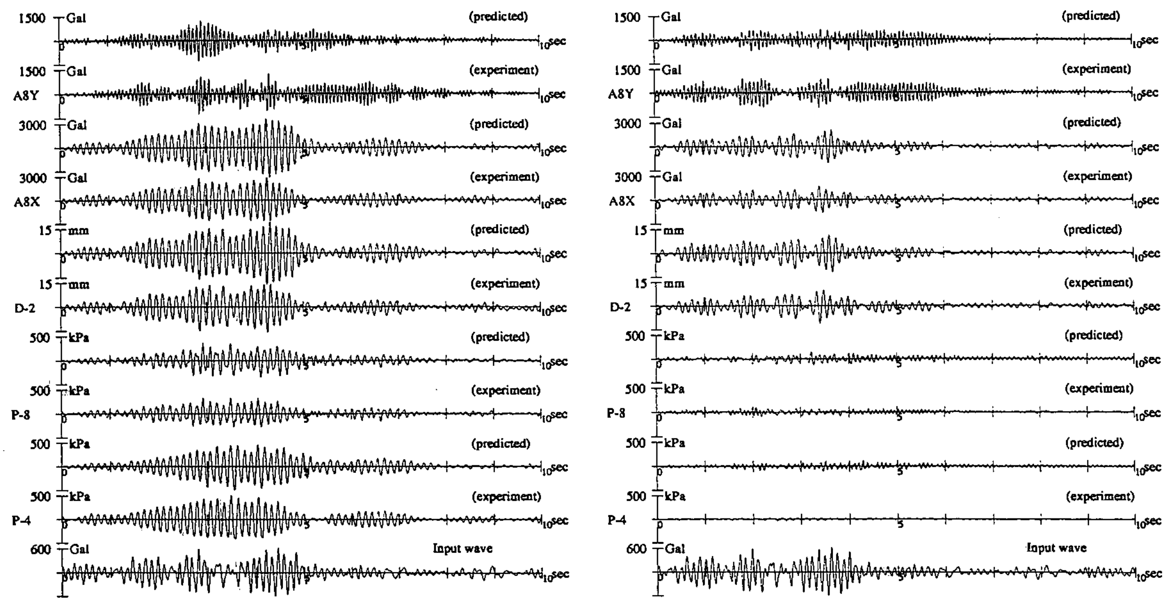


Fig.4 Left : Response curves by experiment and simple two mass model calculation
Right : Measured vibration mode of pressure and acceleration at resonance
(Valve condition No.2, case of weak coupling)



(a) Valve condition No.1

(b) Valve condition No.2

Fig.5 Response waves by earthquake wave excitation and comparison with time history analysis
(used pressure wave propagation velocity = 940 m/s)