Piping Extreme Dynamic Response Studies

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Summary

A piping dynamics research program on the high-loads response of multiple-support piping systems is described. The intent of the research is: to increase the very limited damping data base at response levels near and above the Operating Basis Earthquake (OBE) levels for various support conditions; to drive the pressurized systems to well above their design stress conditon; and to benchmark nonlinear analyses methods. Preliminary results with one simple system are reported.

1. Introduction

Current U.S. design rules for nuclear power piping systems impose what are believed to be very conservative standards with respect to dynamic loads. A result of such conservative practices is costly, heavily restrained piping systems often requiring large numbers of snubbers to provide dynamic restraint while permitting the necessary thermal expansion. Current stress criteria are based on maintenance of prescribed ductile failure margins derived from static load data. For dynamic loads, very limited data have shown that margins against ductile failure are much higher than for a static load of equal magnitude. An additional source of conservatism is damping values stipulated by regulatory authorities for use in dynamic analyses.

This paper describes a piping dynamics research program investigating piping design and involving the erection and high-loads dynamic testing of multiple-support piping systems in a laboratory. Results are presented for an initial phase of testing with a relatively simple, three-support pressurized piping run. Current plans are outlined. The intent of the research effort is: to increase the very limited damping data base at response levels near and above Operating Basis Earthquake (OBE) levels with varying support conditions; to stimulate recognition of safety margins inherent in current design rules by driving pressurized systems to multiples of the input amplitudes required to achieve the design stress condition, inducing permanent deformation; and to provide a benchmark data base for validating nonlinear dynamic analysis methods.

2. Dynamic Test Facility

The test program concept is that of supporting prototypical piping systems on supports that are in turn dynamically driven by powerful hydraulic actuator systems. In this manner, realistic piping designs incorporating typical support hardware can be dynamically excited with a wide range of inputs and simulate the seismic load path, i.e., dynamic motion of support "hard points", in turn exciting piping response. Figure 1 shows a schematic of the test facility with a representative piping system in place. The facility consists of a rather massive, heavily reinforced concrete U-shaped strong-wall structure (note cut in foreground), three to five hydraulic actuators, necessary pumping and accumulator capacity, and control systems. A specimen piping system is mounted on unidirectional sleds, each driven by an actuator, with actuator reaction forces sustained by the concrete strong wall. The sleds serve, in essence, as miniature uniaxial shake tables supporting the pipe at a particular location with suitable hardware.

The facility's initial capacity for earthquake studies is illustrated in Figure 2. This figure compares a response spectrum computed from a sled's time history to a response spectrum used in the design of a nuclear power plant sited in the eastern United States. The spectrum based upon measured motions was calculated from data taken during preliminary studies (discussed below) with a relatively short piping run--7 m x 11 cm diameter. Since even higher capacity is desired for testing larger systems to multiples of allowable stress conditions, the hydraulic system has recently been upgraded.

Instrumentation used in testing includes high-range accelerometers, displacement and load cells, and strain gauge arrays at selected locations. Some 64 channels are supported in the current configuration, with digital data acquisition via a 256-Kbyte 16-bit minicomputer system. Suitable amplifiers and filters condition the analog signals prior to digitization.

3. Results to Date

Preliminary investigations have been conducted to validate test system design, determine desirable modifications, and to demonstrate the dynamic testing techniques while providing data on the response of a relatively elementary piping system.

The selected test specimen was a 6-m (20-ft) run of ASTM grade A-106 carbon steel piping, approximately 11.5 cm in outside diameter (4 in. Schedule 40). The piping run was a Z-shape in a vertical plane with two elbows and up to three supports (reference Figure 3). Dynamic inputs for high-level testing were applied to the piping through motion of the piping supports that were in turn driven by hydraulic actuators providing earthquake-like excitation to the support hardware.

The piping run was excited to varying response levels while under the Code maximum allowable internal pressure (at room temperature) of 102 atmospheres (1,500 psig). The piping run was tested with a variety of support conditions at the midpoint support location. These conditions included: no support, struts of differing stiffnesses, a box frame allowing pipe axial slippage, mechanical and hydraulic snubbers, and supports (strut, snubbers) that failed during the course of earthquake-like time histories.

The testing proceeded in three phases: Phase I and II were conducted with new piping runs of identical geometry, while Phase III tests were conducted with the same piping that was used in Phase II. The piping in Phase I testing was subjected to a sequence of four earthquake tests inducing nonlinear response in the piping system, with peak input accelerations ranging from 1.2 g (linear regime) to 14.5 g (maximum input), inducing peak responses exceeding 22 g, and a maximum uniaxial strain of approximately 150% of the yield strain. In the Phase II and III testing, an identical piping system was subjected to a total of five dynamic tests above the elastic range of the piping material and above the ASME Class 2 faulted stress limit, i.e., allowable stress that might be appropriate for Safe Shutdown Earthquake (SSE) loading.

Figure 4 shows a comparison between one test's achieved input response spectrum for a seismic test and the input necessary (determined experimentally) to achieve the maximum acceptable stress condition*. Thus, the test inputs were some three to four times greater than the input that would have generated the maximum tolerable response by applicable design rules [1].

While the preliminary testing was demonstrating feasibility of the approach and extreme response benchmarking data, the tests were extended to examine damping variations as a function of midpoint snubber support type and piping response amplitudes. Damping values were obtained using the log decrement method and using data acquired during the free vibration period following the sudden imposition of a step displacement at all three pipe support points. As shown in Figure 5, the piping system response was dominated by the first mode response of about 7 Hz, allowing use of the log decrement method. This method appears to provide the "best" estimate for damping in systems that exhibit minor nonlinearities. Even very modest nonlinear behavior can result in damping overestimates when using Fourier transform bandwidth, and underestimates when using sinusoidal sweep response bandwidth [1].

Table I shows the results of the damping studies based upon the average of damping calculated from pipe response at four different locations. The trend for a single location was

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*$2.4S_h$; now is lesser of $3.0S_h$ or $2.0S_y$ for Level D condition.

similar. In general, apparent damping was somewhat higher at higher response amplitudes with hydraulic snubbers apparently inducing somewhat more apparent energy dissipation than the mechanical snubber tested. The issue of damping variation will be the subject of future tests.

4. Future Activities

A ferretic steel pressurized piping system, similar to the layout in Figure 1, is the subject of current work*. It will later be replaced by a system with one main and two branch lines, supported on five high-capacity sleds (dynamic load points). Various support hardware will be installed. Instrumentation will consist, initially, of 64 channels of accelerometers, displacement and strain gauges, and load cells. Multiple strain gauge rosettes will be placed around selected cross sections to extract pipe section dynamic moments from dynamic elastic strains.

The sequence of experiments will be as follows:

- study of damping characteristics associated with multiple supports, alternative support hardware and location, and sensitivity to response amplitudes at stress levels at and above OBE design values;
- execution of earthquake simulations in the elastic and inelastic response regimes for computer program benchmarking; and
- extreme response testing to examine capacity at response levels exceeding SSE stress limits, including effects of one or more support failures.

Current plans involve testing with water at design pressure and ambient temperature. Elevated temperature testing would be possible by substituting a heat-transfer fluid for water and providing suitable heating and removable insulation.

References

[1] ANCO Engineers, Inc., Dynamic Response of Pressurized Piping Systems Tested Beyond Elastic Limits and with Support Failures (Draft), Prepared for the Electric Power Research Institute, Palo Alto, California (February 1983).

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*Joint participation by Safety and Analysis Department, Nuclear Power Division, Electric Power Research Institute (Dr. H.T. Tang, Program Manager) and Civil/Mechanical Engineering Department, Division of Engineering Technology, Office of Regulatory Research, Nuclear Regulatory Commission (Dr. John O'Brien, Project Officer).

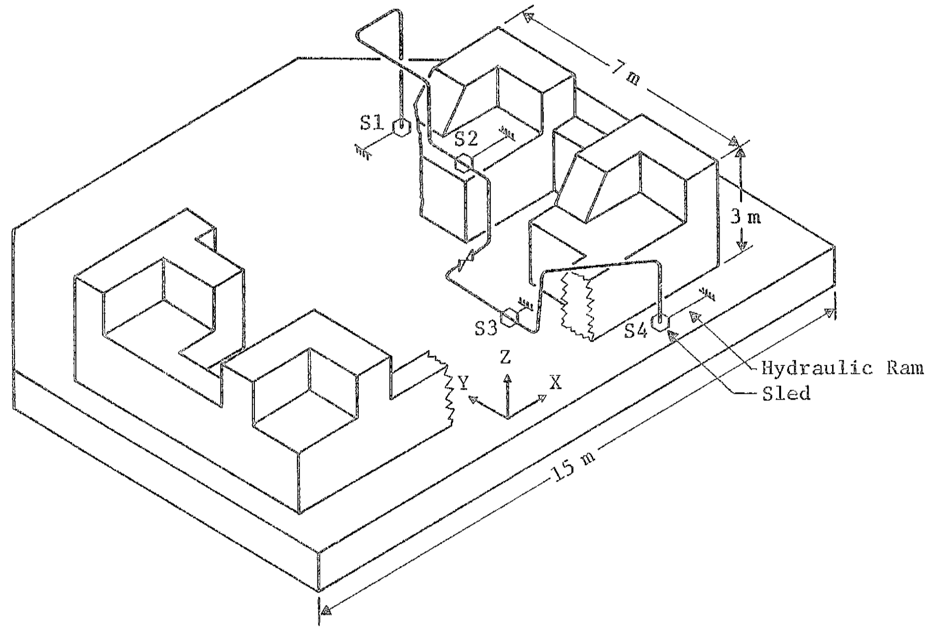


Figure 1: Test Facility with One Piping Configuration

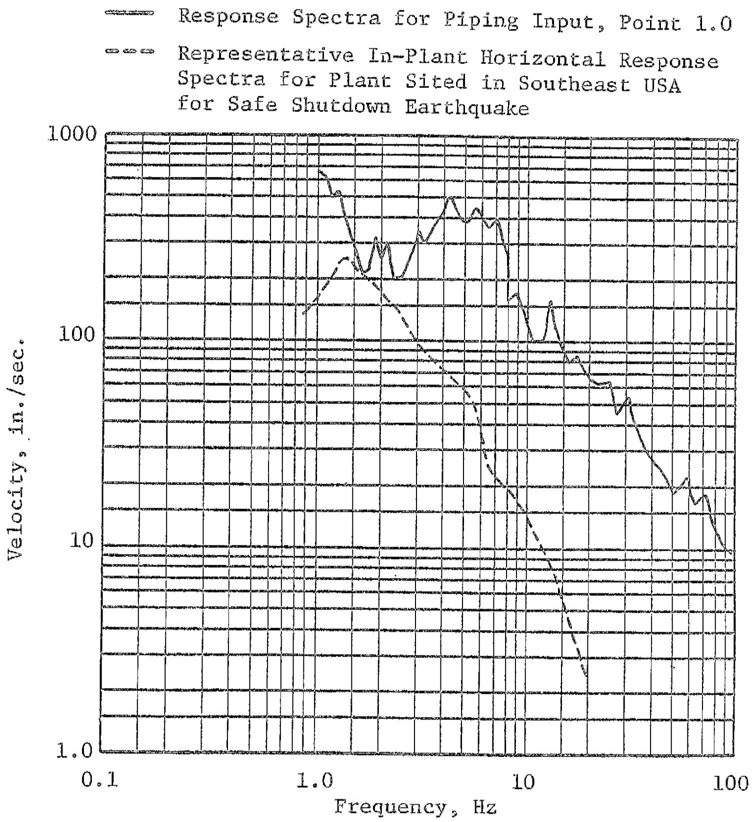
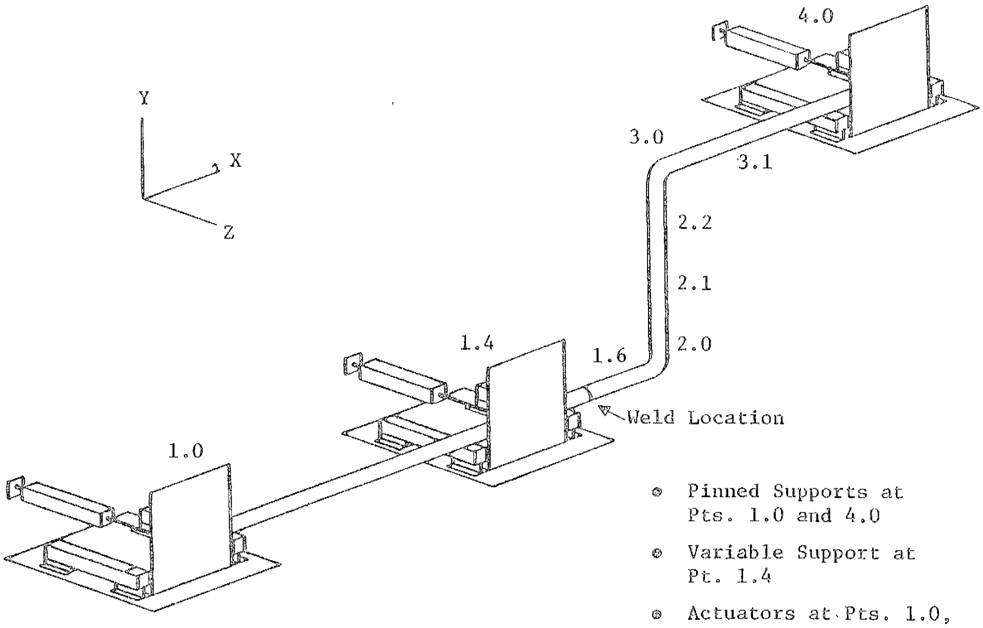


Figure 2: Example Input Response Spectra, 2% Damping



- Pinned Supports at Pts. 1.0 and 4.0
- Variable Support at Pt. 1.4
- Actuators at Pts. 1.0, 1.4, and 4.0

Figure 3: Schematic of Sled and Z-Pipe Setup

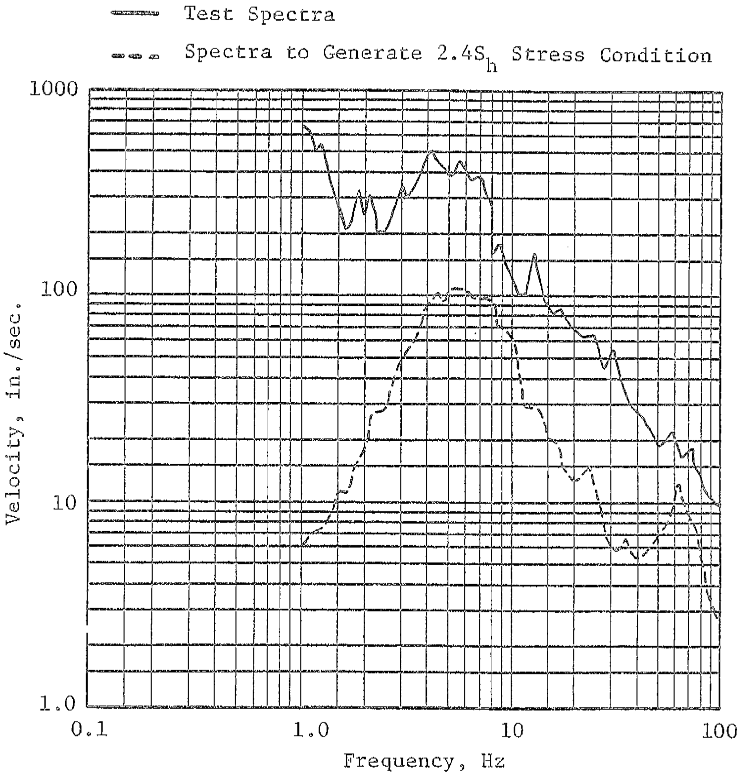


Figure 4: T1R5 Spectrum Compared to That Which Would Produce $2.4S_h$ Stress Condition (2% Damping)

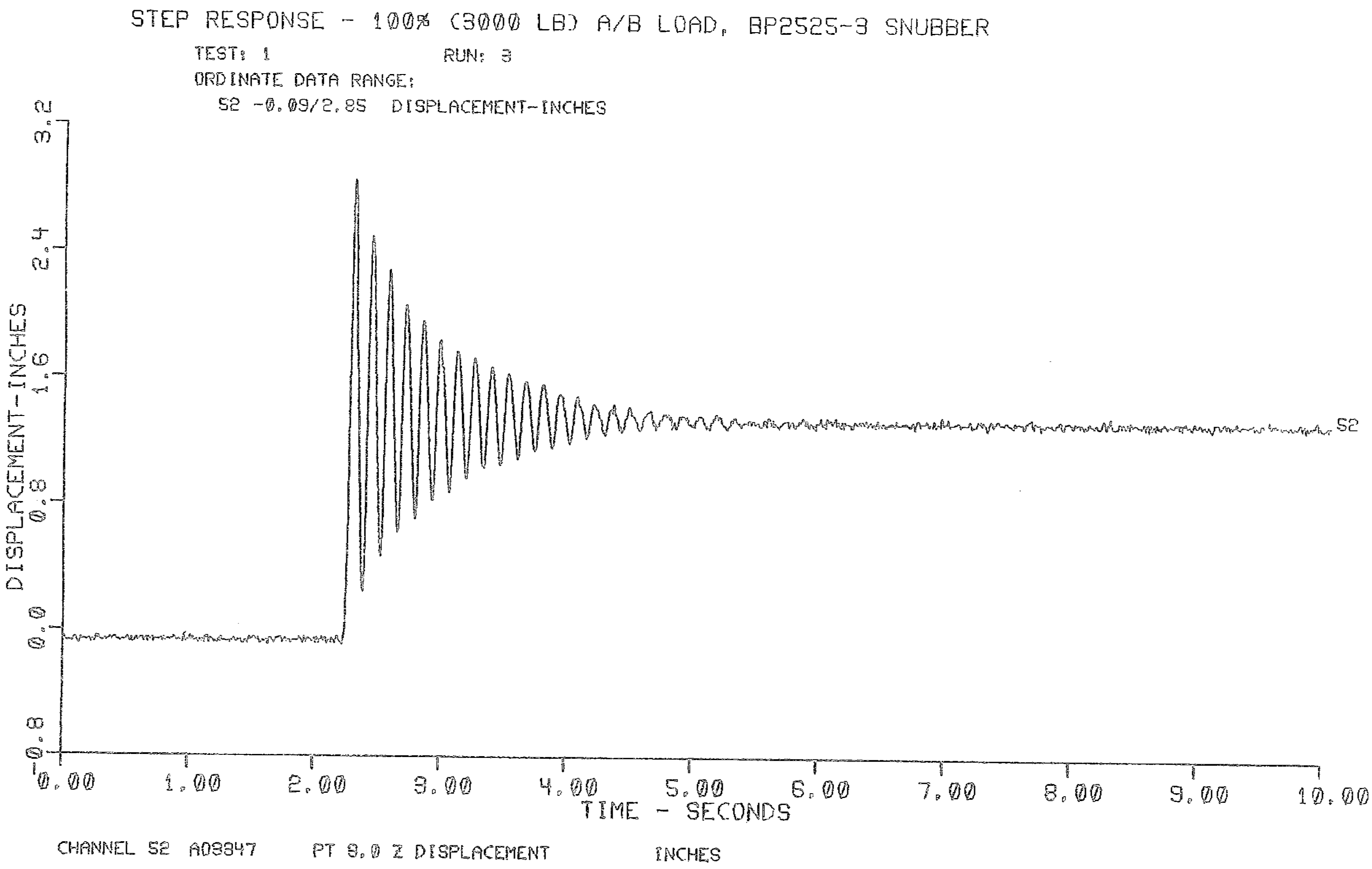

STEP RESPONSE - 100% (3000 LB) A/B LOAD, BP2525-3 SNUBBER
TEST: 1
RUN: 3
ORDINATE DATA RANGE:
52 -0.09/2.85 DISPLACEMENT-INCHES
DISPLACEMENT-INCHES
3.2
2.4
1.6
0.8
0.0
-0.8
52
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
TIME - SECONDS
CHANNEL 52 A08847
PT 8.0 Z DISPLACEMENT
INCHES

Figure 5

TABLE I

AVERAGE LOG DECREMENT DAMPING (FIRST MODE)

Z-Bend Support Type	Excitation Level Damping (%)*			Excitation Level 2 Damping (%)*		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
Rigid Link (Breakable)	**			1.9 ± 0.3	1.8 ± 0.1	1.7 ± 0.2
				(2,300 lbf; 29.2 mm; 9.3 g; 605 με)		
PSA-1 Snubber	1.6 ± 0.1	2.2 ± 0.1	2.3 ± 0.1	2.4 ± 0.3	2.2 ± 0.2	1.8 ± 0.1
	(1,250 lbf; 13.4 mm; 4.6 g; 395 με)†			(2,200 lbf; 27.2 mm; 9.3 g; 590 με)		
Grinnell Snubbers	2.7 ± 0.1	3.1 ± 0.1	2.9 ± 0.1	3.0 ± 0.2	3.1 ± 0.2	3.1 ± 0.1
	(1,600 lbf; 18.4 mm; 4.3 g; 470 με)			(3,300 lbf; 51.0 mm; 10.9 g; 1,040 με)		
Bergen-Patterson Snubber	2.3 ± 0.2	2.8 ± 0.2	2.7 ± 0.0	4.0 ± 0.3	3.8 ± 0.1	3.5 ± 0.1
	(1,300 lbf; 13.0 mm; 3.2 g; 350 με)			(2,700 lbf; 38.8 mm; 8.7 g; 773 με)		

*The damping values presented in this table are average values and the corresponding variations from average. The data used to calculate the average damping were taken from displacement channels corresponding to locations Pt. 2.0Z, Pt. 2.1Z, Pt. 3.0Z, and Pt. 3.1Z.

**Tests of the breakable rigid link were not performed at a lower level of excitation.

†The quantities in parentheses, ( ), are the peak (maximum) support load (at Pt. 1.4), peak relative displacement (Pt. 3.0Z), peak absolute acceleration (Pt. 3.0Z), and peak strain (Pt. 3.0/+Z face of pipe/axial gauge).