PNC TG033 82-01(6)

FIELD INSITU VIBRATION TESTING OF JOYO HEAT TRANSPORT SYSTEM PIPING

Tatsuya Inoue and Hiroshi Taniyama

Experimental Fast Reactor Division,
Oarai Engineering Center, PNC

February 1982

This document is prepared for the Third Japan/USSR Seminar on Methods of Testing of Equipment, Structural Materials and Fuels of JOYO, BOR-60 and BR-10, Tokyo, Japan, February 15-18, 1982.

POWER REACTOR AND NUCLEAR FUEL DEVELOPMENT CORPORATION

PNC TG033 82-01(6)
Feb, 1982

FIELD INSITU VIBRATION TESTING OF JOYO HEAT TRANSPORT SYSTEM PIPING

Tatsuya Inoue and Hiroshi Taniyama
Experimental Fast Reactor Division,
Oarai Engineering Center, PNC

Abstract

Recently most Japanese nuclear plants have examined the appropriateness and correctness of the piping design by field insitu vibration testing. This testing has also become a necessary step in the construction of safe and reliable nuclear plants in seismic areas in the world. For the experimental fast reactor, JOYO, the major piping routes of the reactor coolant system have been tested as one of the functional test programs performed after the construction of the plant. The forced vibration testing method using electromagnetic exciters and applying sine beat excitation to the loop of the layout of the piping system was mainly employed. Field vibration testing is one of the best means to verify design adequacy and to facilitate licensing related to seismic problems. The vibration modes and eigenfrequencies obtained from the test strongly coincide with the analized data. The damping factor varying from 2.5% to 20%, which is higher than the design value(0.5, 1.0%), were measured. From those results the design adequacy and the structural integrity of the pipings have been confirmed at seismic event point of view.

FIELD INSITU VIBRATION TESTING OF JOYO HEAT TRANSPORT SYSTEM PIPING

Table of contents

Introduction

Recently most Japanese nuclear plants have examined the appropriateness and correctness of the piping design by field vibration testing. This testing has become a necessary step in the construction of safe and reliable nuclear plants in seismic areas in the world. For the experimental fast reactor, JOYO, the major piping routes of the reactor coolant system have been tested as one of the functional test programs performed after the construction of the plant.

The forced vibration testing method using electromagnetic exciters and applying sine beat excitation to the loop of the layout of the piping system is mainly employed. Field vibration testing is one of the best means to verify design adequacy, to facilitate licensing related to seismic problems, and occasionally to uncover unexpected problems like effect of mechanical play.

The JOYO primary piping system is of the double-walled structure, while the secondary one is of the single. The inner and outer piping are welded to the lugs at each supporting point. When the earthquake occurs, the motions of them become gradually independent in proportion to the distance from the point. This testing does not include the measurement of the relative vibratory motion, though the measured data may contain the effect of the outer piping motion in addition to that of the inner one.

1. Testing Purpose

The purposes of the field vibration testing of the piping system are confirming the seismic design adequacy by the field excitation experiment. The following items are to be obtained:

(1) Determination of the dynamic parameters, such as eigenfrequencies, damping factors and mode shapes used in a seismic analysis
(2) Verification of the adequacy of an analytical model, parameters like mass and flexibility, and boundary conditions from design viewpoint; and
(3) Firmness of testing equipment or structures and method acceptable to standardize.

2. Tested Pipings and Test Types

2.1 Tested Pipings

One of each piping line in the following systems were tested:

(1) Primary Main Coolant System
(2) Secondary Main Coolant System
(3) Primary Auxiliary Coolant System
(4) Secondary Auxiliary Coolant System
(5) Primary Argon Cover Gas System
(6) Secondary Argon Cover Gas System

This report is related to tests for the systems (1) and (2) above.

2.2 Test Types

The man-made excitations and the electromagnetic exciter are employed to vibrate the piping system alternately. The former is used for the auxiliary system, i.e. the primary and the secondary auxiliary coolant and the argon cover gas system, the latter for the primary and the secondary main coolant system.

3. Testing Method

The JOYO piping systems were tested by imposing vibration with the electromagnetic exciter. Sinusoidal exciting frequencies of 2 Hz to 30 Hz were applied with a sweep time of approximately 20 minutes.

During the performance of this test the exciting force was maintained constant. The signals from the acceleration sensors on the piping were continuously recorded on a multi-channel magnetic tape system through an integration circuit for batch processing. In the integration circuit, sinusoidal acceleration data was converted to velocity with a 90 degree phase shift to obtain flat signal-noise ratio over the frequencies tested.

Acceleration sensors for the secondary coolant system piping were installed on blocks directly attached on the piping, while for the primary coolant system piping they were installed on lugs attached to the piping for supporting elements. Three sensors were installed on each block to measure three directional accelerations.

Resonant frequencies on each sensors were read on the screen of the real time spectrum analyzer.

Sepctrum peaks and relative motions on the sensors were compiled to determine the significant vibration modes corresponding to the resonant frequencies. This was done by processing the magnetic tape data through a low pass filter to kill mechnical noise. The records were processed with a spectrum analyzer after the test was finished. Figure 1 shows the block diagram of the data acquisition system.

Forces applied on the primary and secondary piping systems were 200 kg (440 lb) and 100 kg (220 lb) respectively. The exciting force magnitudes were based on exciter capacity, and safety considerations of testing piping while flowing sodium.

In the primary loop, the exciter was mounted on a base especially prepared for the test. In the secondary loop, the piping was vibrated by exciter suspended by cables, and change of direction of the exciting force was done by turning it. The exciting force was limited by the exciter inertia. Figure 2 shows the exciter installation on the primary piping.

The pipe runs tested were selected such that they were representative of the piping in the complete primary and secondary systems. And an environmental conveniency of the testing was also considered.

Figures 3 and 4 show the pipings tested on the primary and secondary loops. The primary loop piping is 20 inch/22 inch diameter double walled piping with wall thickness of 9.5 mm and 3 mm, respectively. The secondary piping is 12 inch diameter with wall thickness of 10.3 mm.

Danping values were obtained from the sinusoidal decay curves of the individual sensors during free periodic vibration. The free periodic vibration was initiated by cutting off the rope tension with which the piping was drawn. A special trigger device was used to provide quick release of the tension.

4. Theoretical view

The piping systems are designed by the response spectrum modal analysis method.

(1) Eigenvalue

The eigenvalue of the system is determined using the following kinematic equation of free vibration without damping.

$$[M]\ \ddot{\mathbf{U}} + [K]\ \mathbf{U} = 0 \qquad (1)$$

Since free vibration is a harmonic vibration, the displacement can be rewritten as $\mathbf{U} = \mathbf{q}e^{i\omega t}$. Substituting this into Eq. (1):

$$(-\omega^2 \mathbf{M} + \mathbf{K})\ \mathbf{q} = 0 \qquad (2)$$

To get the solution of Eq. (2) with $\mathbf{q} \neq 0$, the following relation must be maintained.

$$|-\omega^2 \mathbf{M} + \mathbf{K}| = 0 \qquad (3)$$

Solving this, the eigenfrequencies are obtained.

(2) Response Analysis

The system response results in the appearance by the following procedures using the response spectrum modal analysis method when the seismic input $\mathbf{P}(t)$ excites the system.

$$[M]\ \ddot{\mathbf{U}} + [K]\ \mathbf{U} = \mathbf{P}(t) \qquad (4)$$

Transforming the kinematic equation expressed in Eq. (4) to Eq. (5) to distinguish the response displacement $\mathbf{U}x$ from the forced displacement $\mathbf{U}y$:

$$\begin{bmatrix} Mxx & Mxy \\ Myx & Myy \end{bmatrix} \begin{Bmatrix} \ddot{U}x \\ \ddot{U}y \end{Bmatrix} + \begin{bmatrix} Kxx & Kxy \\ Kyx & Kyy \end{bmatrix} \begin{Bmatrix} Ux \\ Uy \end{Bmatrix} = \begin{Bmatrix} 0 \\ Py \end{Bmatrix} \qquad (5)$$

Futhermore, expressing Ux with the form of linear combination by mode matrix $\mathbf{p}$.

$$\mathbf{U}x = \mathbf{p}\,\mathbf{\Phi} = [\mathbf{p}_0\ \mathbf{p}_e] \begin{Bmatrix} \mathbf{\Phi}_0 \\ \mathbf{\Phi}_e \end{Bmatrix} \qquad (6)$$

Using orthogonality relations, $\mathbf{p}_0^T \mathbf{M}\, \mathbf{p}_e = \mathbf{p}_e^T \mathbf{M}\, \mathbf{p}_0 = 0$, substitute Eq. (6) to Eq. (5) the following kinematic equation without coupled vibration occurs:

$$\ddot{\Phi}_e + \alpha^2 \Phi_e = -\frac{p_e^T M p_e}{p_e^T M p_e^2}\ddot{\phi} = -\beta\ddot{\phi} \qquad (7)$$

where β is participation factor. The solution Φ_e can be obtained.

In the floor response spectrum method, the maximum resultant acceleration and displacement of each mode are calculated using the maximum modal value determined by the floor response spectrum and finally composed by means of the root mean square method as follow.

$$\left.\begin{aligned} \ddot{U}xj &= \beta \ddot{\Phi}_j p_j \\ Uxj &= \beta \ddot{\Phi}_j / \omega_j^2 p_j \end{aligned}\right\} \qquad (8)$$

$$\left.\begin{aligned} \ddot{U}x &= \sqrt{\sum_{j=1}^{n} \ddot{U}xj} \\ Ux &= \sqrt{\sum_{j=1}^{n} Uxj} \end{aligned}\right\} \qquad (9)$$

5. Test Result

In the primary coolant system, the piping was excited vertically because cell space and difficulties of mounting an exciter did not allow vibration input to the piping to be applied horizontally.

During this test, it was found that in some hydraulic snubbers reactions were nullified because of their mechanical plays which existed at mechanical joints under the low exciting force applied. And all hydraulic snubbers were replaced with pipe rods of one inch in diameter to minimize the play. This replacement was done in order to test the piping with the supposed piping support condition for the design earthquake. In the design, hydraulic snubber is assumed to be rigid to block the axial displacement on the piping against quick motion while it does not restrain the piping against slow motion of thermal travel.

The test was performed successfully showing that the dynamic behavior of the piping corresponded to the calculated behavior including vibration mode and resonant frequency. However the vibration modes corresponding to the eminent spectrum peaks appeared in the high frequency range were not related to the analysis significantly. Because horizontal acceleration signals were not high enough to assess the dynamics in the high frequency range especially at positions far from the exciting point for the piping was excited vertically, and sensors were restricted to be installed on the lugs to obtain the response of the inner piping, which were welded to both inner and outer walls of the double walled piping.

In this test a resonant frequency at a nominal 11 Hz which corresponded to the first eigenfrequency analyzed was obtained though an eminent spectrum peak appeared at lower frequency range. An example of the spectrum obtained from this test is shown in Figure 6.

To investigate the cause of this low spectrum peak, an analytical survey was performed.

This was done by applying existing equivalent spring constants of the pipe rods on the analysis, while the eigenfrequencies of the piping system were calculated assuming that the hydraulic snubbers had infinite spring constants in the design.

The equivalent spring constant was determined by measuring the load imposed on the pipe rod and axial displacement of the piping at the resonant frequency. The load was measured by strain gauges on the pipe rod and the displacement was evaluated from the acceleration measured at the node on the piping.

The values of equivalent spring constant were smaller than the spring constants of the pipe rods themselves and sensitive to the nodal displacement because of remaining mechanical play.

Higher damping values were obtained in the tests than the value used for the design. These values varied from around 2.5% to 6%.

During these free periodic damping tests, frequency spectra were also measured. It was noted that the similar frequency spectra to those of sweep vibration were obtained.

In the secondary coolant system three directional exciting forces X, Y and X were applied to the piping. Figure 7 shows a typical spectrum obtained on the secondary piping. Comparison of the test and analytical results of vibration characteristics is described in Table 1.

The modes of vibration were determined by tracing the relative displacements of the sensing positions corresponding to the earliest three resonant frequencies.

The modes obtained here differed from ones analyzed, therefore an analytical survey on the piping was also performed applying the equivalent spring constants of existing hydraulic snubbers available during the test.

The analysis showed good correlation between analytically surveyed and tested vibration modes including eigenfrequencies. Figures 8 and 9 show analytically surveyed and tested vibration modes on the primary and secondary eigenfrequencies.

Also large damping values were obtained on the secondary piping varying from around 3.5% to 20%. Figure 10 shows an example of damping value obtained on the secondary piping.

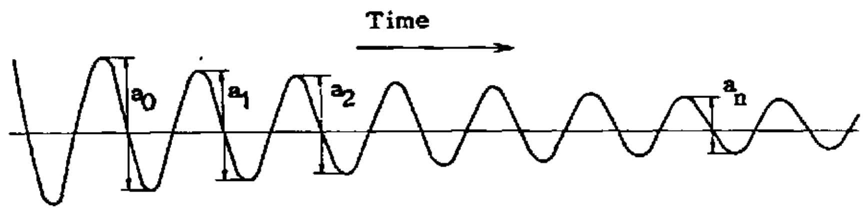
Sinusoidal beat of the piping was successful and the vibration of the piping was sinusoidal accordingly through the frequencies testd. The high frequency mechanical noises which appeared on the sensor signals were killed in the filter circuit.

The data acquisition system demonst.ated excellent performance through the tests.

Notes:

(1) The damping values adopted for the primary and secondary piping design are 1% and 0.5%, respectively. The conservative low damping value was adopted for the secondary coolant system pipings because they constitute containment boundary inside of the containment vessel.

(2) The damping value is de,ined as follows:



$$\text{Damping Value} = \frac{1}{2\pi}\left(\frac{1}{n}\log_e\frac{a_o}{a_n}\right)$$

6. Conclusions

Through these tests the restraint effect of hydraulic snubbers under the small nodal displacements was a principal concern in evaluating the validity of the seismic design. It is not practical to vibrate the piping with input excitation at high enough levels to overcome all of the mechanical play in the snubbers.

The analytical survey showed that the vibration modes of piping system were sensitive to the stiffness of snubbers, especially on the piping system which is arranged three dimensionally. Accordingly, the field vibration tests were performed under a condition given with finite snubber spring constants.

The JOYO piping system integrity from the stand point of seismic design was confirmed by showing that the actual stresses under design earthquake load were less than the calculated values. This was done by showing larger existing damping values than the values adopted for the design of the piping, and correlation of piping dynamics between tested and analyzed ones.

It is acceptable to assume that hydraulic snubbers will function as rigid piping restraints under the design earthquake which will impose large potential nodal displacement on the piping, and the piping will behave as analyzed so long as the computer program for the analysis is applicable.

The computer program applicability was verified by showing good correlation between the tested and analytically surveyed piping dynamics.

The damping values obtained on both primary and secondary coolant systems seem to have sufficient margins to account for uncertainties in the dynamic behaviors of the pipings under the design earthquake.

Memo

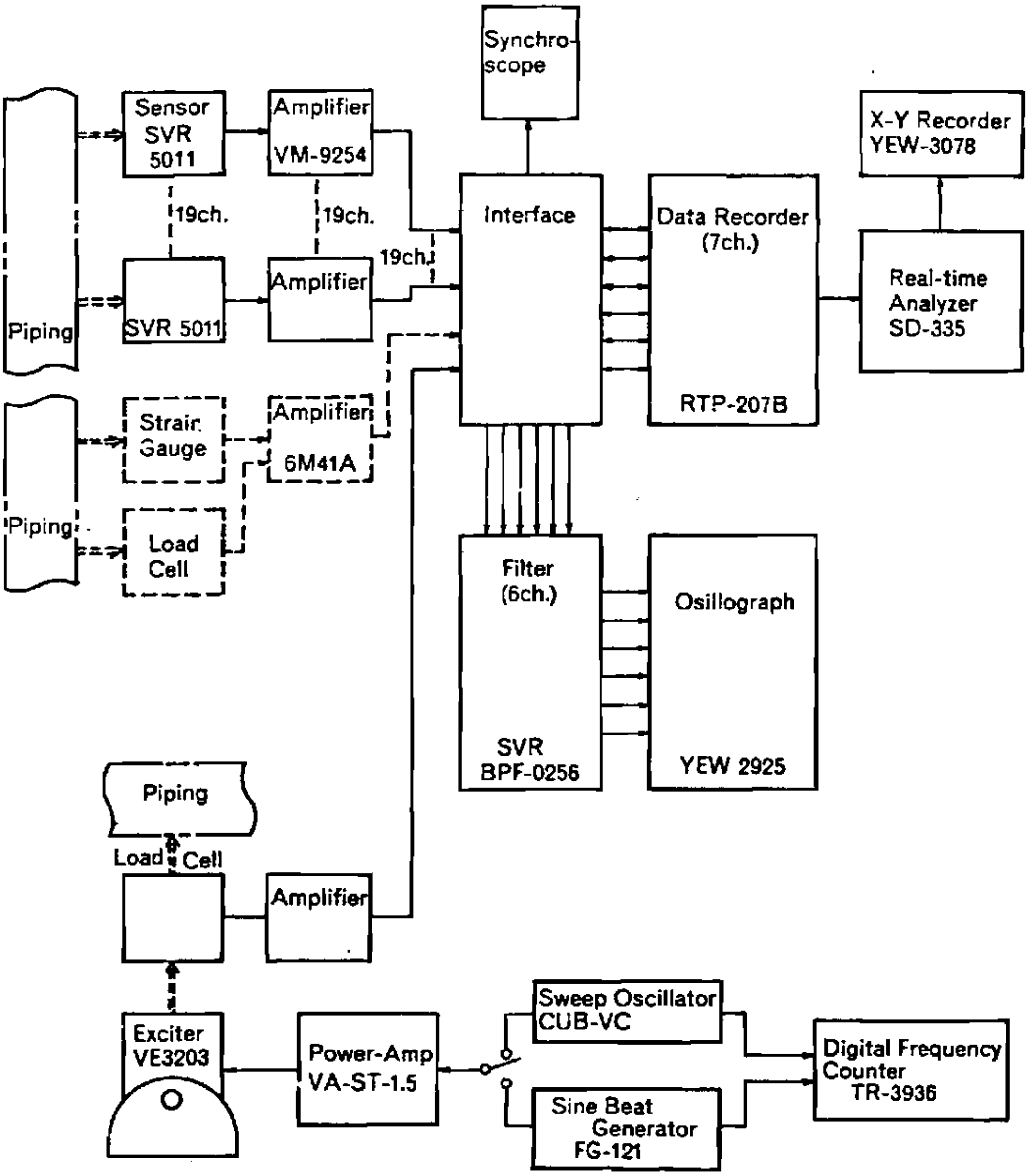


Fig. 1 Block Diagram of Data Acquisition System

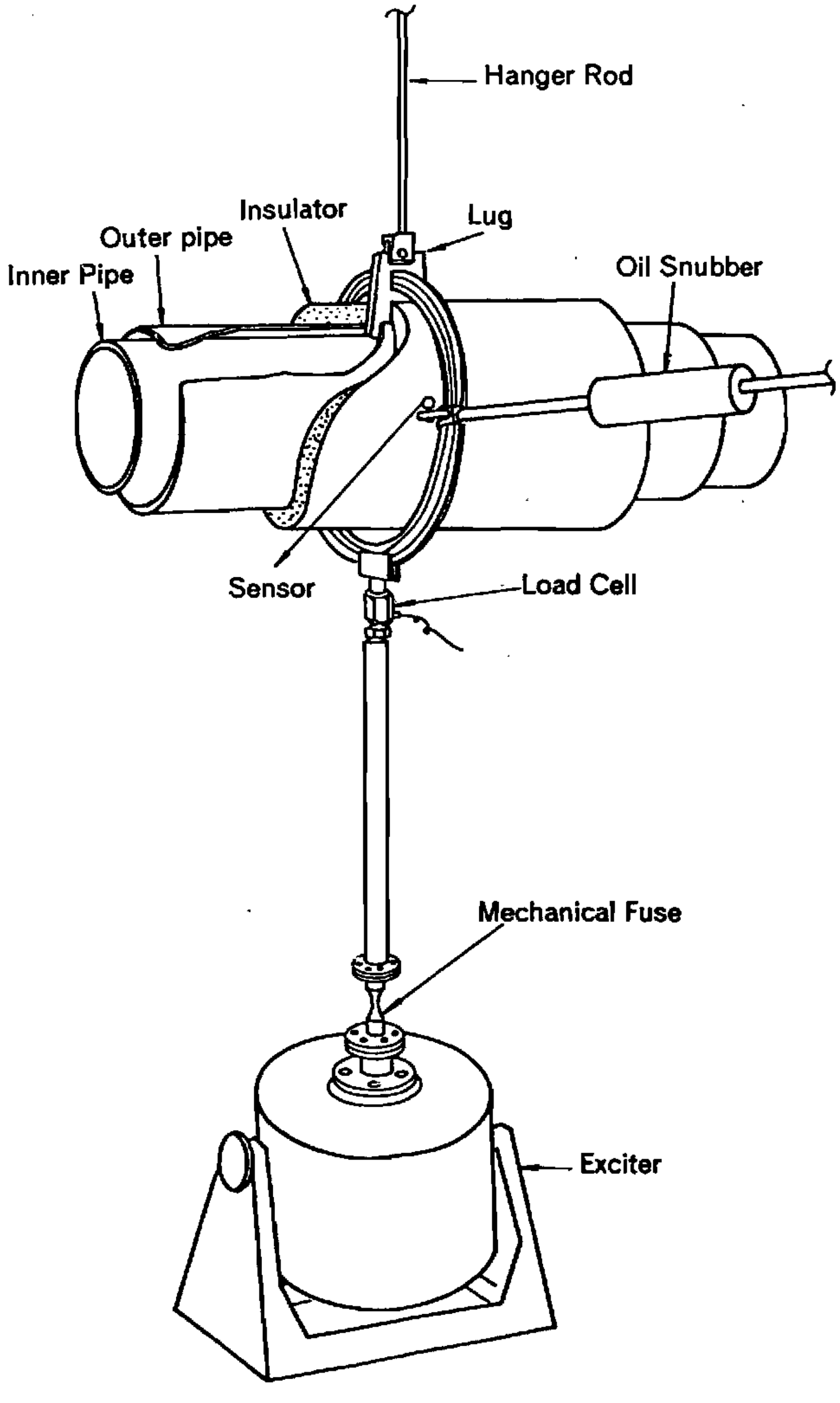


Fig. 2 Exciter Installation on the Primary Piping

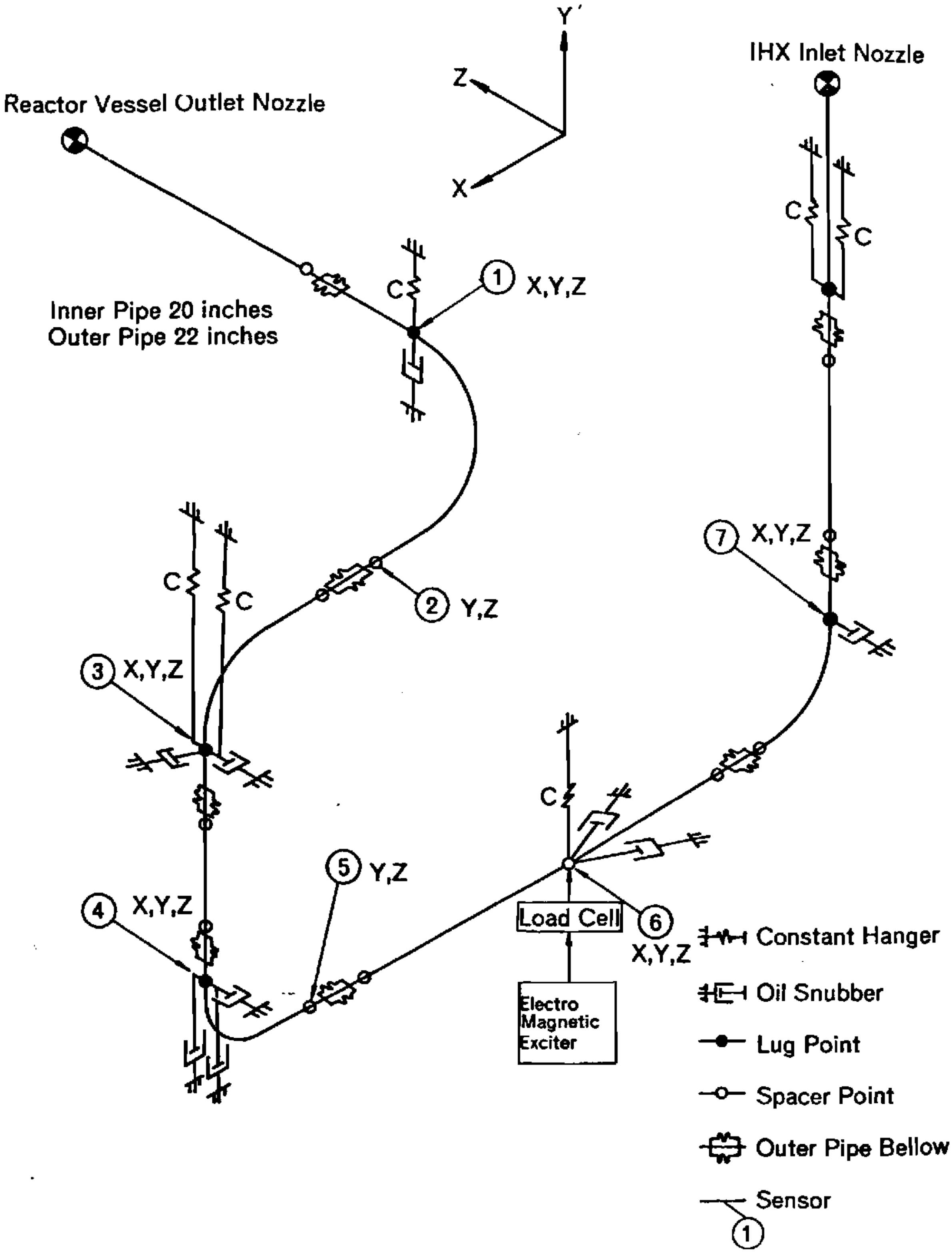


Fig. 3 Piping Tested on the Primary Loop

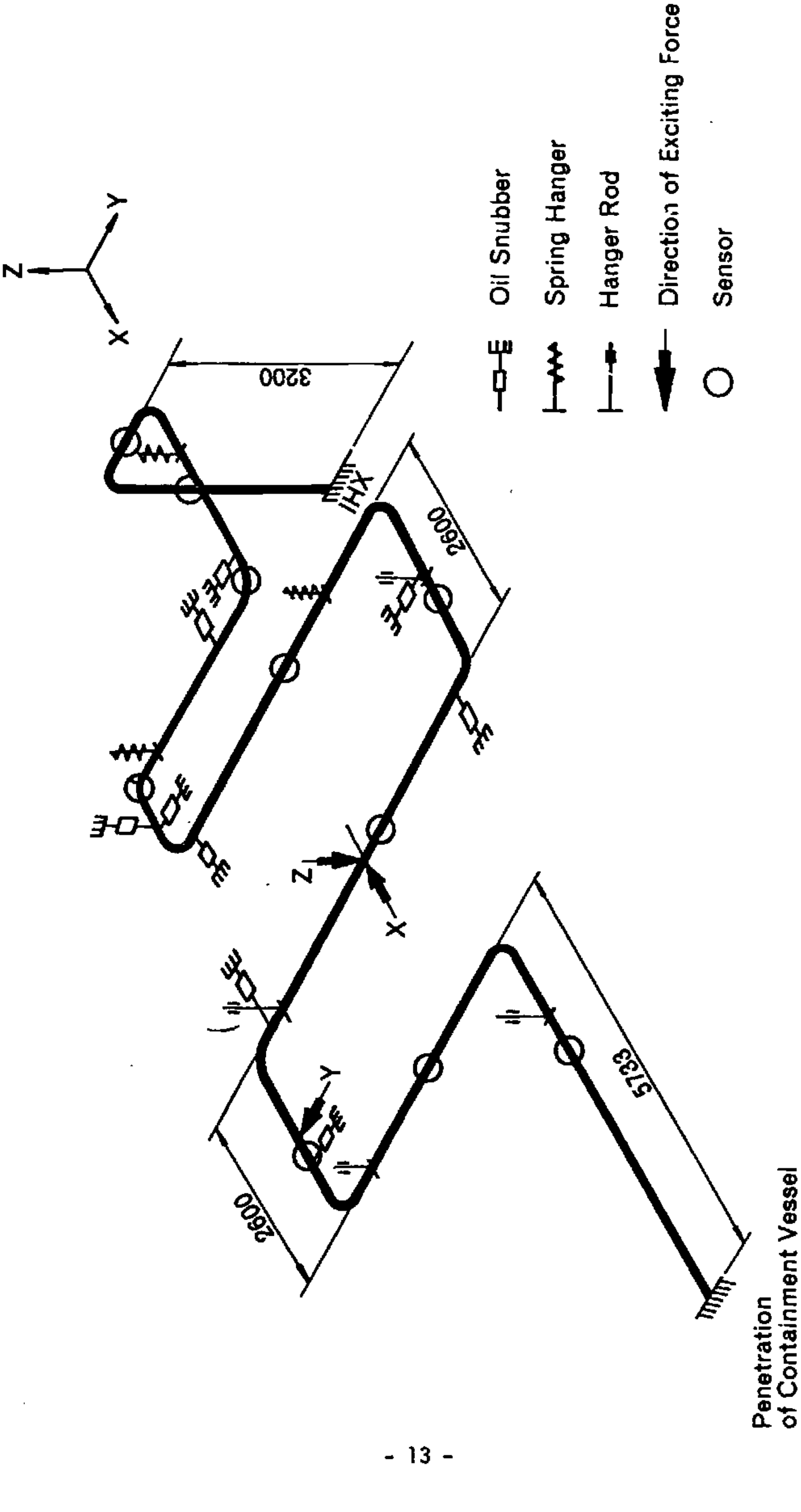


Fig. 4 Piping Tested on the Secondary Loop(12 inch)

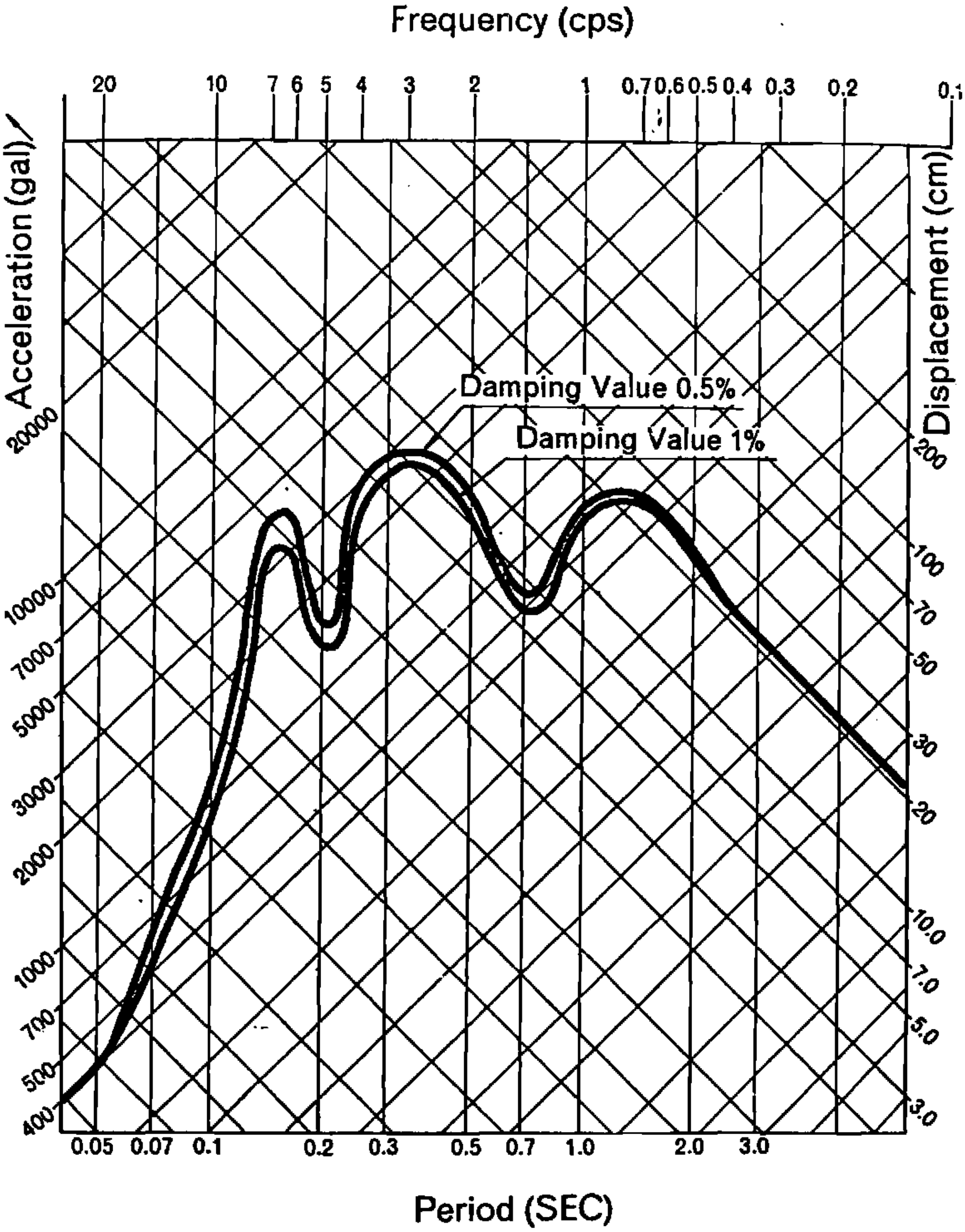


Fig. 5 Example of Floor Response Spectrum Applied to JOYO's Seismic Design

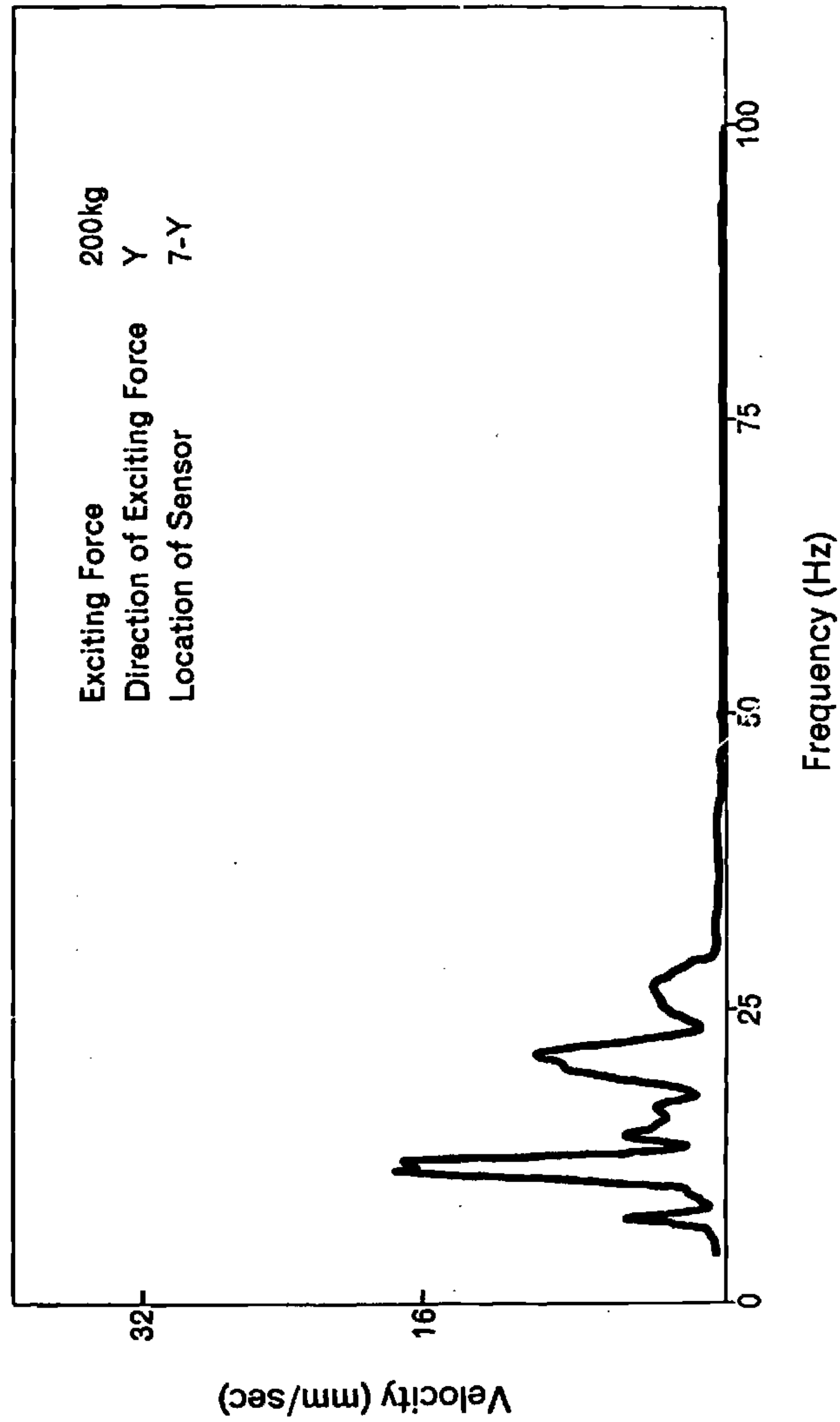


Fig. 6 Typical Response Spectrum on the Primary Piping

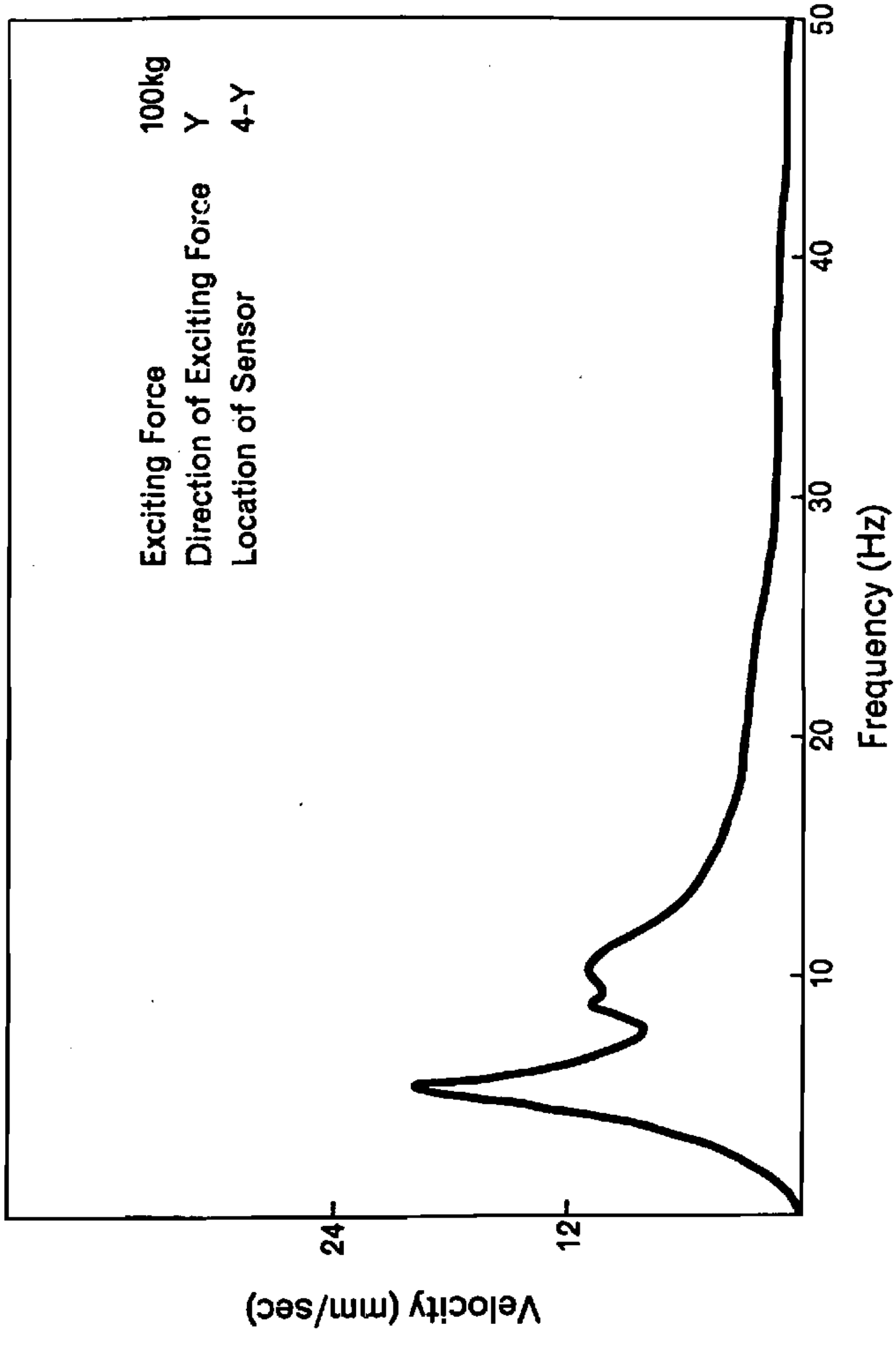
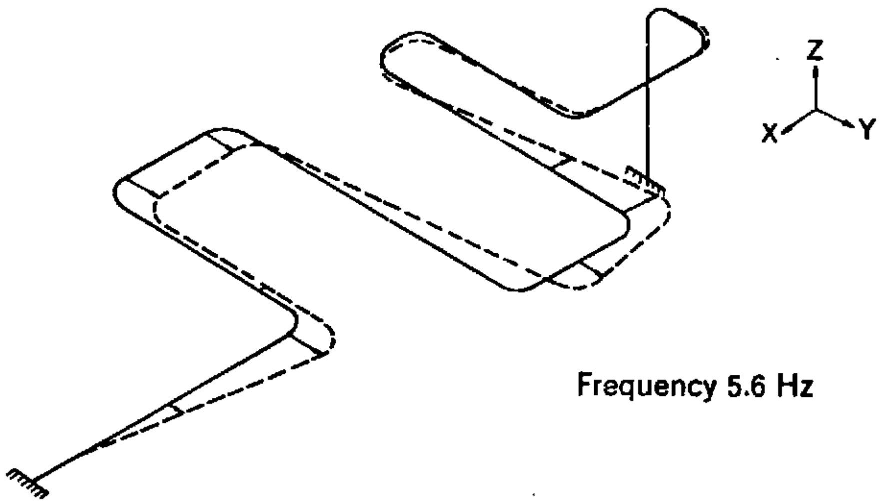
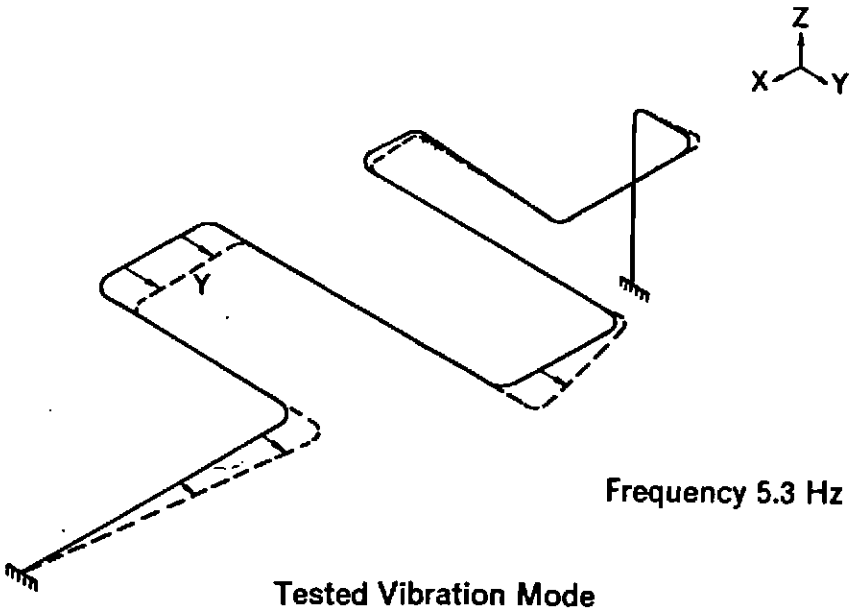


Fig. 7 Typical Response Spectrum on the Secondary Piping

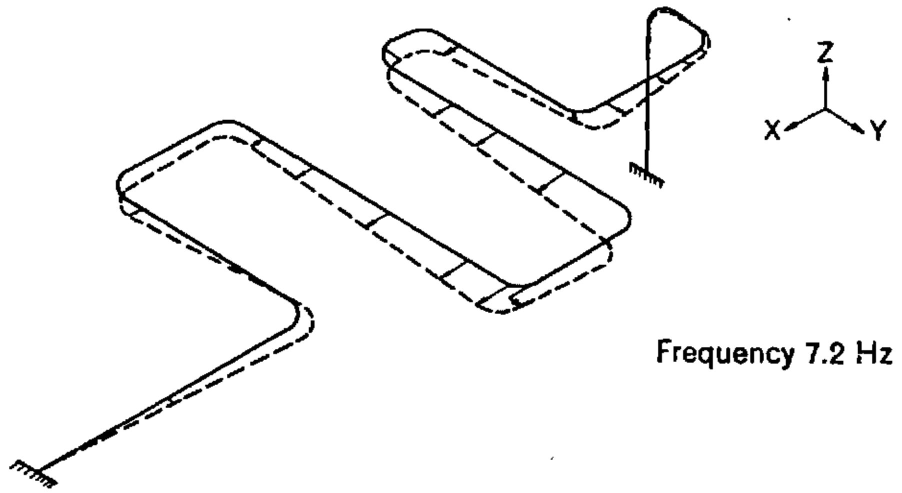


Calculated Vibration Mode

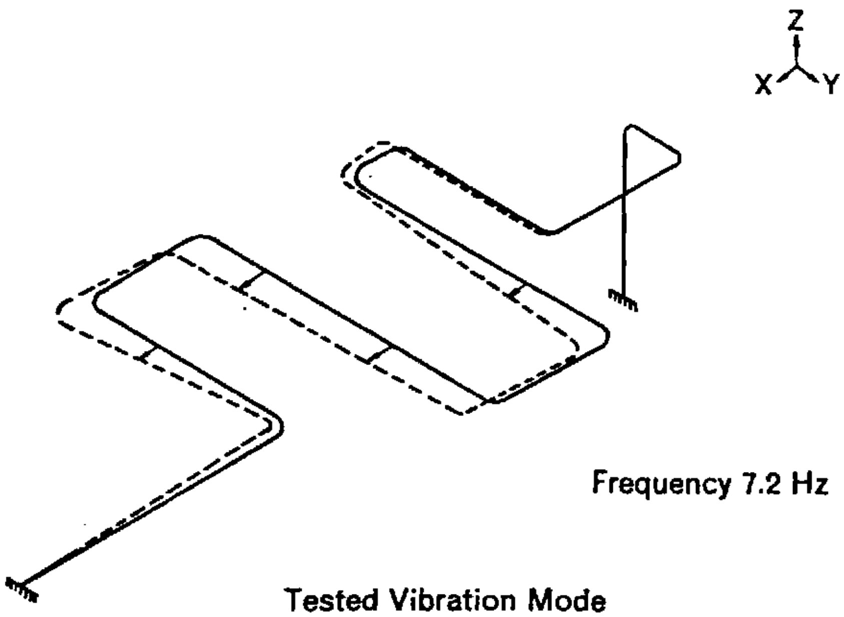


Tested Vibration Mode

Fig. 8 Comparison of Analytically Surveyed and Tested Piping Dynamics



Calculated Vibration Mode



Tested Vibration Mode

Fig. 9 Comparison of Analytically Surveyed and Tested Piping Dynamics

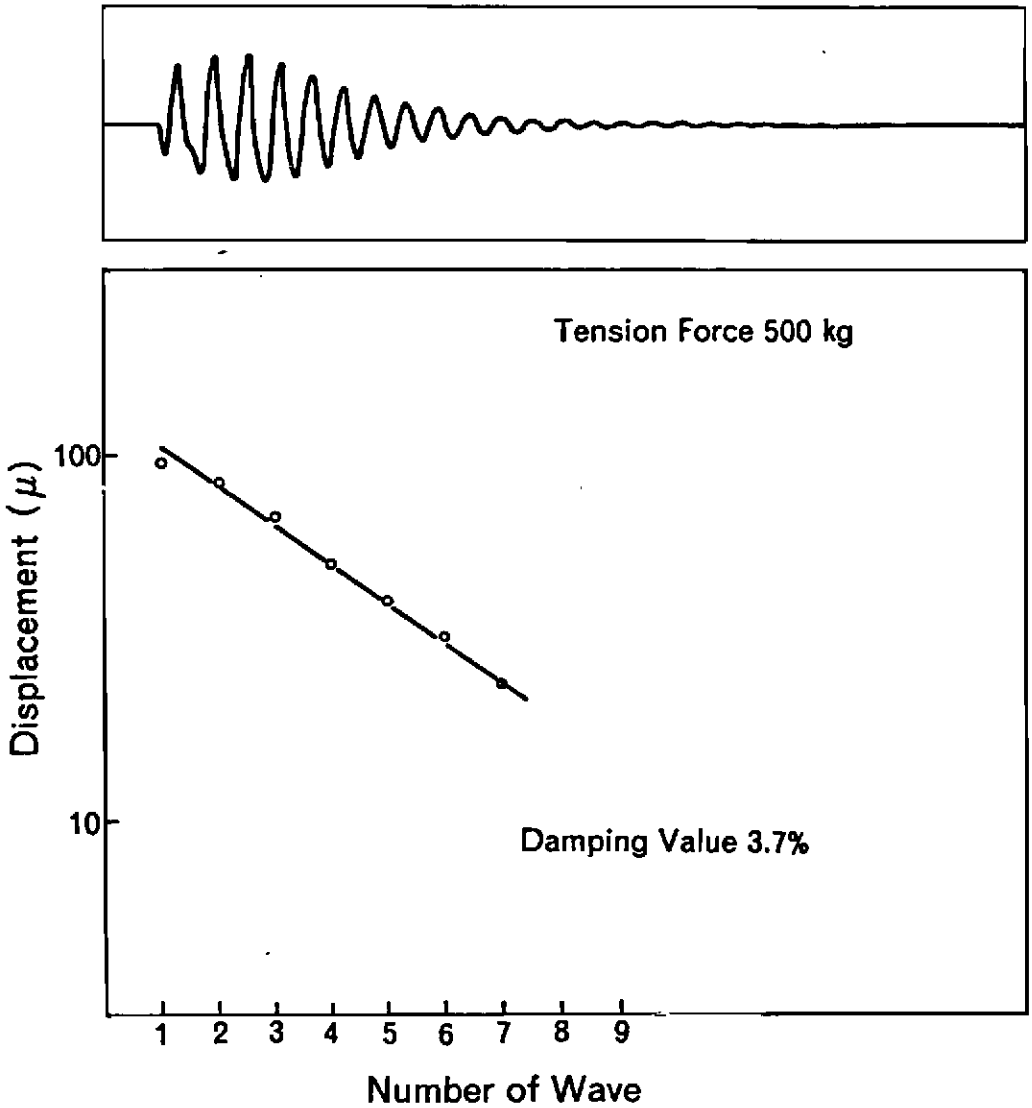


Fig. 10 Wave Form and Damping Value Obtained During Free Periodic Vibration

Table 1 Test and Analytical Results of Secondary Coolant System Piping Vibration Chracteristics

Mode	Eigenfrequency, Hz			Damping Factor, %	
	Test Result	Analytical Result			
		Rigid Snubber Model	Spring Snubber Model	Test Result	Design Value
1	5.3	5.9	5.6	17.5 - 18.2	0.5
2	7.2	7.5	7.2	14.8 - 22.4	0.5
3	8.3	11.1	7.8	---	0.5
4	8.8	12.3	10.1	3.7 - 5.3	0.5