1982 ASME Winter Meeting
Phoenix, Arizona

DYNAMIC RESPONSE OF PIPING SYSTEMS AT VARYING LOAD AMPLITUDES: EXPERIMENTAL STUDIES OF DAMPING

George E. Howard, William B. Walton, Daniel E. Chitty, Paul Ibáñez
ANCO Engineers, Inc.
Culver City, California

H. T. Tang, Y. K. Tang
Electric Power Research Institute
Palo Alto, California

ABSTRACT

Beginning in 1979, ANCO Engineers began a series of analyses and tests of a nuclear power plant piping system (feedwater system in Consolidated Edison of New York's Indian Point) to investigate the dynamic characteristics of such a system. The ultimate goal of the research effort is the development of improved analysis methods for piping systems subjected to dynamic loads. The subject piping, 20 cm (8 in) in diameter and 33.5 m (110 ft) in length, had a vertical rise of approximately 15 m (50 ft) and fourteen elbows and eight restraint locations between anchor points (see Figure 1). Among the major objectives of the research were investigations of piping system damping and nonlinear phenomena as a function of response amplitude, and the development of benchmark data for validating nonlinear analysis methods.

The subject piping system was investigated with the following boundary conditions:

- essentially as built--the as-built system with an ANCO-designed anchor installed at the top end to isolate attached equipment from the subject piping--(Phase I);
- essentially as-built, with insulation removed (Phase II);
- with all original restraints removed between anchors and "modern" restraint systems installed (Phase III), including
  - --one configuration consisting entirely of relatively rigid struts;
  - --two configurations combining mechanical snubbers and struts; and
  - --one configuration combining hydraulic snubbers and struts.

A typical "modern" restraint configuration consisted of three to four snubbers combined with eight struts distributed between system anchor points. The "modern" identifier refers to restraint systems which are designed in accordance with current seismic design practice. (The modern support system was designed by EDS Nuclear, San Francisco.) The ASTM A106 Grade A piping was excited to response stresses exceeding 75% of yield at selected locations, peak displacements exceeding 6 cm (2.4 in), and peak accelerations exceeding 5 g.

TEST METHODS

Two experimental techniques were used to excite the piping system to the desired response levels: sine dwell (sinusoidal excitation at precisely controlled frequencies); and snapback (initial displacement, quick release tests). Both methods applied known forces to the piping at selected locations; snapback testing dominated the test sequences. Sine dwell testing imposed forces up to 3,000 lbs, while force levels as high as 13,500 lbs were applied in the snapback testing.

One hundred data channels of piping system response were monitored, recorded, and processed on-site by a minicomputer system and, subsequently, stored on magnetic media for later use. The data channels varied during the testing in the various phases. During Phase III (the "modern" restraint system), they were as follows: 13 triaxial accelerometer arrays; 4 biaxial displacement transducer arrays; 13 load cells in pipe supports; and 10 nodal arrays of strain gages with 4 gages per array. (The strain gage array installation and recording were provided by Philadelphia Electric Company (PeCo), Philadelphia, Pennsylvania.) The strain gage geometry was selected such that the three components of moment could be extracted from the strain measurements, assuming that the axial force and the two shear forces were negligible at the measured node.

In addition to providing piping moment response data for subsequent use in benchmarking piping design computer programs, the strain-induced moment data provided the means for monitoring the experiment for piping "safety." Safety was defined in terms of acceptable imposed stresses at the monitored locations, with stresses computed (given three moments) from the ASME code equations for Class II piping systems. Since the piping was unpressurized and subjected to neither thermal nor anchor point displacements, the only load sources were the gravity and inertial terms. The definition of the acceptable stress limit so computed during the test program increased in the course of the work according to the circumstances of the host facility (Indian Point 1). Early in the testing, the maximum acceptable imposed stress condition was that which corresponded to a Level B limit ($1.2S_h$, where S_h was 12,000 psi for the material and conditions). During the testing with the "modern" restraint system (Phase III), a Level D ($2.4S_h$) limit was generally applicable.

DATA ACQUISITION

Data acquisition was in a digital format utilizing banks of analog-to-digital converters and minicomputers to process the conditioned and filtered analog signals before disk storage. Because much of the transient data would be further processed with the Fast Fourier Transform (FFT) algorithm, and this algorithm is particularly efficient with data sets in powers of two, $2^{11} = 2{,}048$ points were typically acquired per channel. The choice of time step size was governed by two somewhat conflicting criteria. The Shannon sampling theorem requires that the signal be sampled at at least twice the rate of the highest significant frequency content of the signal; otherwise data distortion (aliasing) will occur. Experience indicates that even higher sampling rates are desirable. Contrary to the desire for faster sampling, long data traces increase frequency resolution in the FFTs and allows improved bandwidth estimates (for damping calculations). If the number of points sampled is N, and the sampling interval Δt sec, the FFT frequency resolution, Δf, is $(N\Delta t)^{-1}$ and total sample time, T, is $(N-1)\Delta t$. For example, if N is 2,048, and Δt is 0.030 sec, then Δf is 0.016 Hz, and T, the total sample time is 61.410 sec. As a general rule, the frequency resolution for adequate estimation of damping must be less than about one-fourth of the spectral peak's bandwidth at the half-power point--that is, five or more frequency points to define the structure of the FFT spectral peak being used for the damping estimate. For example, for a 4 Hz resonance ($f_n = 4$ Hz) and 1% damping ($\beta = 0.01$), the bandwidth ($BW = 2\beta f_n$) is 0.08 Hz; and the frequency resolution should be less than or equal to $BW/4 = 0.02$ Hz. For the above example, this is the case, as the resolution $\Delta f = 0.016$ Hz. Typical sampling parameters are given in Table 1.

SELECTED RESULTS--MODERN SUPPORT CONFIGURATIONS

Achieved Response

Tables 2 and 3 present peak imposed load and pipe response data for all four support configurations--all strut supports (1), mechanical snubber/strut combinations in two geometries (2 and 3), and hydraulic snubber/strut combination (4). Configurations 2 and 4 were identical in geometry, with the only difference being the switching of the hydraulic (Bergen-Pattersen) and mechanical (Pacific Scientific) snubbers (see Table 4 and Figure 1). The indicated peak stress ratios in the tables are referenced to a $2.4S_h$ condition (near or incipient yield)--e.g., a stress ratio of 0.64 implies a stress condition of $1.54S_h$ (64% of yield).

As shown in Table 5, the first two observed frequencies of the piping system (with and without internal water) were similar for the various configurations. During snapback testing, the range of variation in frequency was 5% to 15%, depending upon force amplitudes and configurations. This behavior was, in general, the anticipated result, since snubber function is to lock-up upon high load rates and, thus, behave nominally as support struts. In practice, the snubbers behaved as nonlinear devices, significantly influencing estimated damping (energy dissipation) in the system.

The different configurations all exhibited hardening or stiffening behavior--that is, apparent stiffness increases with increases in imposed force amplitudes. Nonlinear behavior of the various systems was manifested by changes in the system frequencies with response amplitude and the (measured) nonlinear boundary conditions imposed by some of the system's snubbers. Nonlinear forcing imposed on the piping by some of the snubbers was particularly apparent in the transient testing (snapback) time histories of snubber force response at selected locations. Those nonlinearities probably account for the broadening of peaks in frequency-domain plots of system response and, therefore, strongly influence apparent damping estimates based upon the half-power method.

The nonlinear behavior of the system may be seen in the acceleration time histories. Figure 2 shows overlayed acceleration time histories in which a 5,000 lb test is compared to a 10,400 lb test after multiplication by the ratio of imposed load. If the system were linear, the solid and dashed curves would overlay exactly. Location 413,Z (a snubber location, with the snubber in the Z direction) shows significant nonlinear behavior, and the match between the curves is poor from both an amplitude and phase point of view. The match is quite a bit better for location 419,Z; however, there is still a phase difference.

Damping Observations

If the systems described herein were linear, a straightforward presentation of the results would be adequate. All methods of calculating damping would yield essentially the same results, and the snapback and sine dwell tests would be compatible. All the systems tested, however, exhibited some degree of nonlinear behavior; hence, the damping estimated was different for each method used to calculate it.

In calculating damping from snapback test data, three methods were used: (1) log decrement; (2) half-power bandwidth; and (3) least squares (error minimization) fit. The log decrement approach is used with time domain data, whereas the other two methods are used with frequency domain data (FFT data). The nonlinear nature of the systems (softening or hardening) resulted in an increase or decrease of the period over time during the snapback tests (the frequency changed with changing response level). This caused the resonant peaks of the FFT data to be broadened--that is, all the energy corresponding to a particular mode was not at a single value of the corresponding natural frequency. This had the effect of increasing the damping as calculated by the half-power and least squares methods. However, the fact that the period changed with changing response level did not affect the damping calculated by the log decrement method. (This method is only concerned with the number of cycles that have occurred in a time interval and not the period of those cycles.) The log decrement damping calculated would have been the same regardless of the variation of the period with response level. Thus, log decrement damping estimates, determined from the type of nonlinear transient data obtained from this test program, would result in identical linear transient response as a function of cycle number, for the same peak response.

Three methods were also used in calculating damping from the sine dwell test data; they were: (1) half-power bandwidth, (2) least squares (error minimization) fit of a linear model, and (3) two-point fit. The use of these three methods resulted in different values of damping for a substantial number of tests and modes. In some cases, two of the three methods yielded similar results; however, it was not always the same two methods. In comparing the two-point fit models with the sine dwell data, it was observed that there was excellent agreement to the left of the resonant peaks of interest. At frequencies beyond these peaks, there was generally poor agreement; the data had a much lower amplitude (modulus) than that for the model. This tends to suggest a drop-jump phenomenon affected the system response (a behavior of certain nonlinear systems when they are subjected to harmonic loading). In comparing the least squares linear models with the data, it was observed that there was, at best, moderate agreement. In a number of cases, the model peak response was only about 75% of that of the data. Because of the large variation of calculated damping for the sine dwell tests, as determined by the three methods, it is believed that no one method can be relied on to provide accurate estimates of damping from sine dwell data for nonlinear systems. The log decrement damping from transient testing was generally (although not always) greater than the half-power and least squares damping from the sine dwell tests but less than the two-point fit damping.

Conceptually, the least squares (or error minimization) fit methods implemented herein entailed determination of the best linear model to fit the experimental results. Least squares fitting uses all of the frequency data points in an ensemble, not just the half-power and maximum response points. For sine dwell, the method consisted of the following steps shown in Figure 3: (1) from frequency response data (physical space) and an initial estimate of the system modes (assumed not to be the modes to be determined), an initial estimate of the corresponding modal frequency response (modal space) is determined-- this results in a set of transformed data corresponding to a set of single-degree-of-freedom systems; (2) the natural frequencies, modal damping, and modal masses are then determined, which results in a best fit between the predicted modal responses and the modal frequency response data; (3) the improved modes are then determined which result in a best fit between the theoretical and measured physical response; (4) the process described above is repeated, starting with the improved modes until a converged solution is determined. The approach can be used for systems with closely spaced modes.

The last method in this study used to calculate damping was a "two-point fit" method. It was used only for the case of widely spaced modes; it is essential that the response near a modal peak be mainly due to the mode corresponding to the peak (see Figure 4). The method involves determining the damping and effective mass that fit a theoretical frequency response curve through Points 1 and 2 . The theoretical response is for a linear single-degree-of-freedom dynamic system subjected to harmonic forcing. Point 2 is always taken to be at the peak of the curve.

All of the above methods for determining damping were derived using a linear theoretical model. For this reason, they must be used with great care when they are applied to nonlinear systems. Similar methods could be developed for nonlinear systems if adequate models could be developed.

Figure 5 is illustrative of the fitting of a linear dynamic model to sine dwell data using error minimization procedures for Configuration 2. Figure 5 is for a relatively high amplitude test (48 mm or 1.9 in peak displacement at the measurement point); note that the linear model captures accurately the first and second response frequencies but poorly tracks the response curve and overestimates the bandwidth of the peaks and, thus, damping.

Figure 6 illustrates the application of the two-point fit method to Configuration 2 for sine dwell testing. Nonlinearity is particularly apparent here in that a linear model captures the response well below resonance but, naturally, cannot capture the post-resonance plunge that occurs. The smaller peak (at about 4.5 Hz here) adjacent to the resonant peak is typical of nonlinear systems as has been verified by digital, as well as analog simulations of the very simple models.

The following observations were drawn from the data evaluations conducted to date:

- The calculated damping values (log decrement method) are at least double the 1% damping of Nuclear Regulatory Guide 1.61 as applied to subject piping system at the Operating Basis Earthquake (OBE) response level, a very important observation since the OBE condition typically controls the design of piping systems. The use of 2% damping rather than 1% could reduce predicted piping dynamic response by perhaps 20% to 30% for piping with frequencies in the high-floor response region of a structure.

- The logarithmic decrement method appears to be the preferred method for estimating damping in systems with small nonlinearities.

- The estimated first mode damping for all of the "modern" restraint systems varied between 2.0% and 3.5% (using logarithmic decrement method) and was approximately 3.0% in the second mode for all configurations.

- The use of common frequency-domain techniques applied to transient data (such as the half power method) to estimate damping can lead to very high estimates of damping in piping systems in the presence of even small stiffness nonlinearities. These estimates are typically much higher than those based upon log decrement methods and are very sensitive to the presence of stiffness nonlinearities.

- The use of the half-power bandwidth method to calculate damping from sine dwell data usually resulted in lower damping than the log decrement (transient) method for about the same response amplitudes. Since much of the literature appears to report damping values based, to a large extent, on sine dwell test data, it is possible that the influence of nonlinearities in tests previously reported has resulted in lower estimates of test object damping than would have been obtained by log decrement estimates.

Figures 7 and 8 show plotted results of damping estimates based upon the log decrement method.

INFERENCES

The data base developed during the reported testing is the subject of continuing study, and the data regarding support loading and strain gages are in the process of evaluation. Based on the data evaluation to date, it may be stated that the piping system with "modern" supports exhibited nonlinear behavior. This was manifested by changes in the system frequencies with response amplitude and the (measured) boundary conditions imposed by some of the system's snubbers. Nonlinear behavior may also be observed in the inability of a linear model to capture the piping behavior, as well as the amplitude and phase differences observed in superimposed response time histories.

The subtle nonlinearities of the piping system have a very important effect on the damping that one might extract from the data for use with an 'equivalent' linear model of the system. If one calculates damping from sinusoidal test data, the damping calculated is frequently lower than log decrement predictions. If one uses half-power calculations based on transient response data, damping estimates much higher than log decrement values result. While the research is continuing, the work conducted to date does not permit a definitive statement regarding the significance of such nonlinear behavior from either a simulation or design point of view. Such a determination requires, first, the generation of a nonlinear model of the subject piping system which accurately reproduces the observed behavior; second, the excitation of this model with postulated dynamic inputs; and third, a comparison of the piping stresses resulting from the nonlinear simulation with the results of current practice (linear elastic analysis). However, previous studies have shown that such nonlinearities may be very important in accurately predicting system response.

TABLE 1

TYPICAL SAMPLING PARAMETERS (2048 POINTS THROUGHOUT)

Frequency Domain of Interest (Hz)	Step Size, Δt (Sec)	Frequency Resolution Δf (Hz)	Samples/ Sec	Nyquist Frequency (Hz)	Total Sample Time T (Sec)	Filter Cutoff Frequency* (Hz)	Minimum β Observable
1 - 3	.083	.0059	12	6	170.6	4.0	.02
3 - 10	.025	.0196	40	20	51.2	12.0	.02
10 - 30	.0083	.059	120	60	17.16	40.0	.02
30 - 100	.0025	.196	400	200	5.12	120.0	.02

Note: *For 8 pole filters, this gives 20 dB (factor of ten) attenuation at Nyquist and less than 180° error at upper range of frequency of interest. This is usually adequate.

TABLE 2

MAXIMUM RESPONSE FOR ALL SNAPBACK TESTS

Configuration	Test	Force (lbf)	Peak Displacement (mm)	Peak Acceleration (m/s^2)	Peak ASME Stress Ratio
1	S128R1LY	12,400	*	56.7	0.53
2	S238R1LZ	10,400	130.2	68.9	0.79
3	S339R1LZ	9,700	75.3	57.7	0.73
4	S440R1LZ	11,000	80.0	73.9	0.80

Note: *Transducer failure.

TABLE 3

MAXIMUM RESPONSE FOR ALL SINE DWELL TESTS
(Response at First Natural Frequency)

Configuration	Test	Vibrator Eccentricity (kg-m)	Peak Displacement (mm)	Peak Acceleration (m/s^2)	Peak ASME Stress Ratio
1	F16081Z	2.86	*	50.5	0.64
2	F26281Z	3.92	62.0	48.0	0.65
3	F36081Z	2.86	54.5	22.2	0.58
4	F46081Z	2.86	63.0	52.5	0.71

Note: *Transducer failure.

TABLE 4

DIFFERENCES BETWEEN CONFIGURATIONS 1 - 4

Configuration	Node Point				Number of Snubbers
	413	482	541	821	
1	RS*	RS	RS, RS	RS	0
2	MS*	MS	MS, MS	RS	4
3	MS	MS	RS, RS	MS	3
4	HS*	HS	HS, HS	RS	4

Note: *RS, MS, and HS refer to a rigid strut, mechanical snubber, and hydraulic snubber, respectively.

TABLE 5

NOMINAL VALUES OF NATURAL FREQUENCIES

Configuration	Natural Frequencies of Full Pipe (Hz)					
	First	Second	Third	Fourth	Fifth	Sixth
1	4.2	6.8	8.3	12.6	15.4	16.7
2	3.8	6.6	7.75	13.0	14.9	-
3	3.9	6.5	7.7	9.8	12.1	-
4	4.1	6.95	12.5	15.1	17.4	-

Configuration	Natural Frequencies of Empty Pipe (Hz)					
	First	Second	Third	Fourth	Fifth	Sixth
1	4.95	7.9	-	14.8	16.1	18.7
2	4.8	7.7	8.3	15.0	16.2	-
3	4.7	7.65	8.3	-	15.1	18.5
4	4.9	7.95	-	15.35	-	-

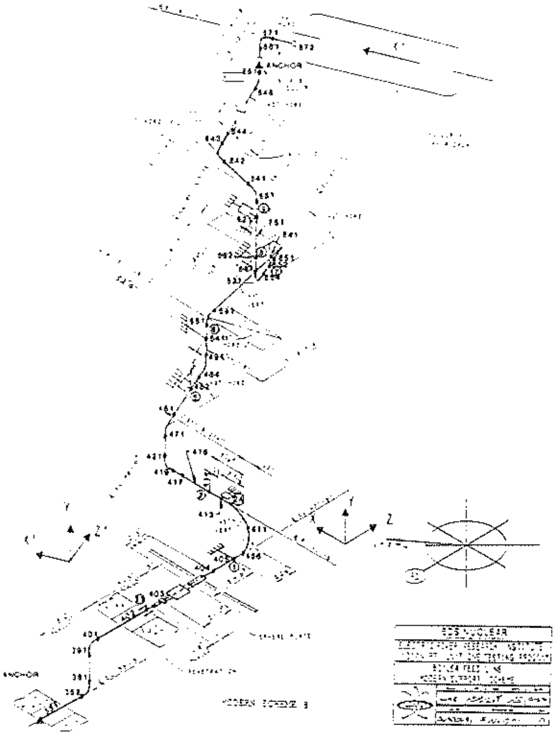


FIG. 1 NODE POINT LOCATIONS FOR PHASE III TESTS AT INDIAN POINT

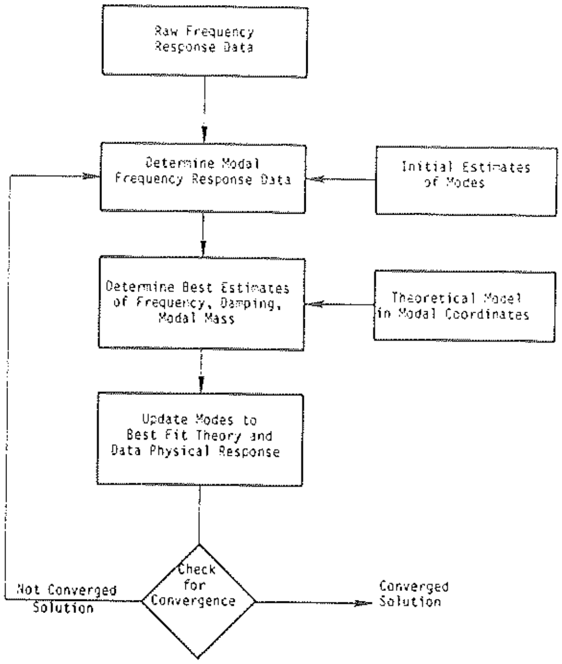


FIG. 3 SCHEMATIC FOR LEAST SQUARES FITTING - SINE DWELL TESTS

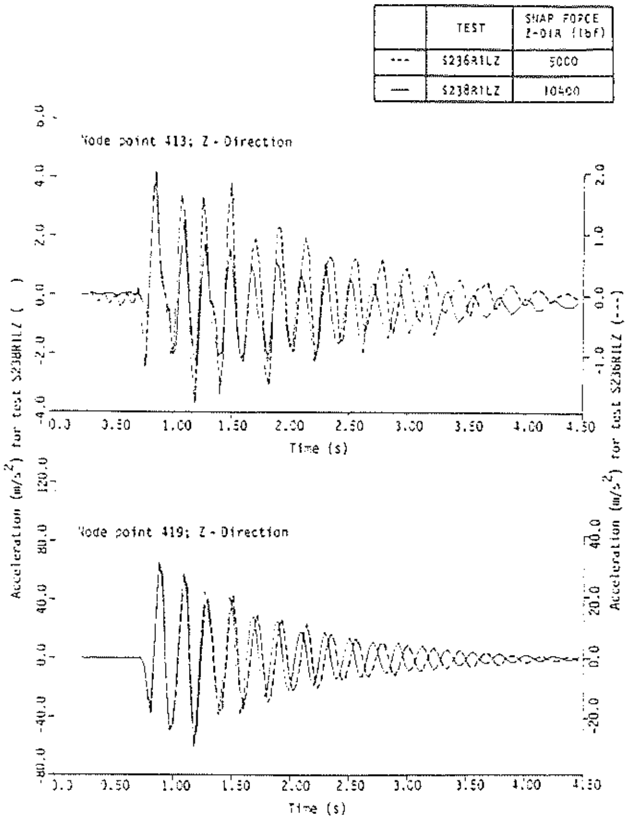
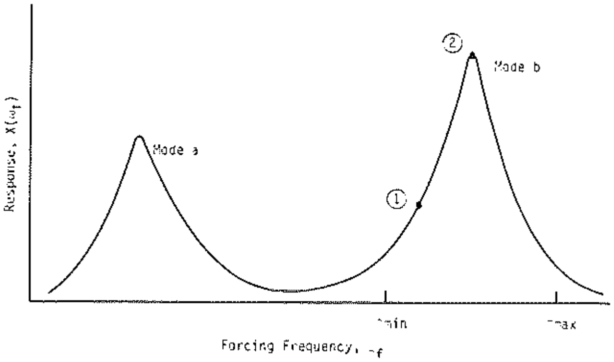


FIG. 2 COMPARISON OF ACCELERATION FOR TWO LEVELS OF SNAPBACK FORCE



(The two point fit method is to be applied within a frequency domain where the response is due to a single mode; i.e., for mode b, method is applied in domain $\omega_{min} \leq \omega_f \leq \omega_{max}$.)

FIG. 4 TWO POINT FIT METHOD FOR SINE DWELL TESTS

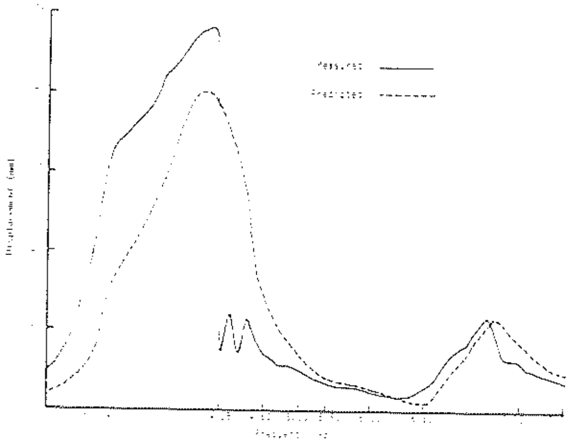


FIG. 5 COMPARISON OF MEASURED AND ANSPI PREDICTED RESPONSE (LOCATION 419,Z), TEST F261R1Z

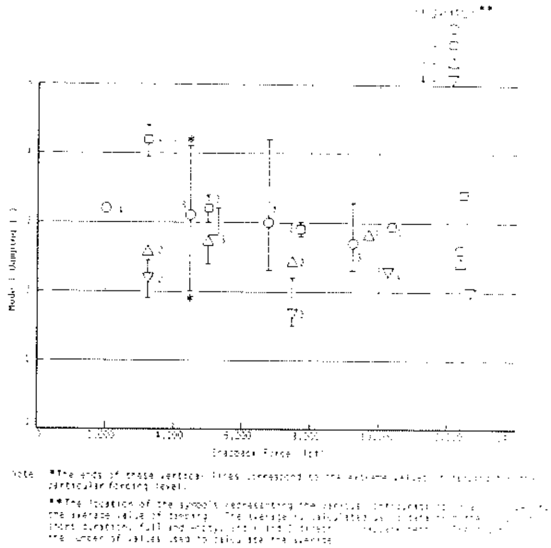


FIG. 7 FIRST MODE DAMPING (LOG DECREMENT) AS A FUNCTION OF SNAPBACK FORCE (LONG AND SHORT DURATION TESTS; Y AND Z FORCING)

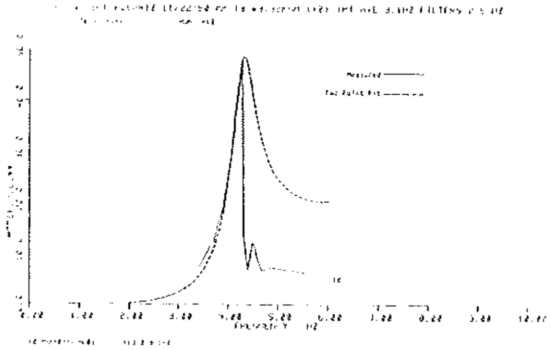


FIG. 6 COMPARISON OF MEASURED AND TWO POINT FIT RESPONSE (LOCATION 419,Z), TEST F26R1Z

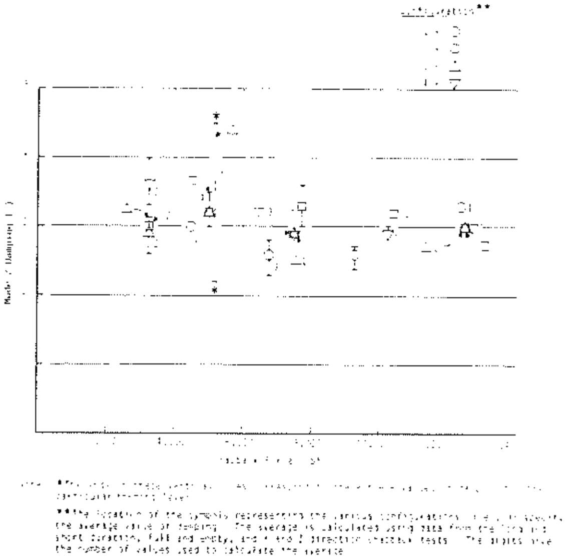


FIG. 8 SECOND MODE DAMPING (LOG DECREMENT) AS A FUNCTION OF SNAPBACK FORCE (LONG AND SHORT DURATION TESTS; Y AND Z FORCING)