Conservatism Inherent to Simplified Qualification Techniques Used for Piping Steady State Vibration

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ABSTRACT

This paper examines some of the qualification techniques currently used by the power industry, including the techniques specified in a recently issued standard related to this subject (ANSI/ASME OM-3, Requirements for Preoperational and Initial Startup Vibration Testing of Nuclear Power Plant Piping Systems). Several methods are used to demonstrate the amount of conservatism inherent in these techniques. Allowable limits calculated by the use of simplified techniques are compared to limits calculated by more detailed computer analysis. A portion of a reactor feedwater piping system along with the results of a piping vibration monitoring program recently completed in a nuclear power plant are used as case studies. The limits determined by the use of simplified criteria are also compared to limits determined empirically through the use of strain gauges.

The simple beam analogies that use vibrational displacement as acceptance criteria were found to be conservative for all the examples studied. However, when velocity was used as a criterion, it was not always conservative. Simplified techniques that result in displacement allowables appear to be the most viable method of qualifying piping vibrations.

Quantities referred to in the paper are cited in British units throughout. These may be converted to the International System of Units (SI) as follows: 1 foot = 0.3048 meter; 1 inch = 0.0254 meter = 1,000 mils; 1 psi = 6,894 pascals; and 1 inch/second = 0.0254 meter/second.

Acknowledgement

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1. Introduction

The objective of this paper is to quantify the conservatism inherent in the simplified qualification techniques used for piping steady-state vibration. Most piping will experience some amount of steady-state vibrations as a result of the flow of the contained fluid or resulting from vibrations of associated equipment. In nuclear power plants these vibrations must be qualified to ensure that a fatigue failure will not result during the 40-year design life of the plant. Governing power piping codes and U.S. Nuclear Regulatory Commission Regulatory Guides contain requirements for considering the effect of piping steady-state vibrations. The predominant way of accounting for these vibrations is to monitor the piping during actual operation. This avoids the need to consider the effect of steady-state vibrations in the design-basis analysis of the piping. Because of the immense amount of piping typically found in a power plant, simplified qualification techniques are needed to keep the task of addressing the vibrations within manageable limits.

Quantifying the conservatism inherent in various qualification techniques will avoid the use of overly conservative or nonconservative criteria. The use of overly conservative criteria will result in needless additional analysis and/or testing or may result in unnecessary system modifications. Conversely, the use of nonconservative criteria may result in piping failures which could have detrimental effects on plant reliability and safety.

2. Simplified Qualification Techniques

Screening methods are used to develop allowable limits for piping vibration. The objective of the screening methods is to provide a simplified means of calculating conservative acceptance criteria for the vibratory response of piping. Various approaches have been used in developing screening methods. [1,2,3] Generally, these methods are based on the assumption that the vibratory stresses in a piping system can be conservatively estimated by dividing the system into smaller segments and using a simple beam analogy to estimate the vibratory stresses. The fundamental vibration modes of the simple beam models are used to derive the acceptance criteria. The acceptance criteria are further based on limiting the peak vibratory stresses to a value less than or equal to the stress endurance limit for the piping material. Since a continuous 10-hertz vibration can result in greater than 10^{10} stress cycles over the 40-year design life of a power plant, the effective endurance limit for power piping would be a peak stress allowable corresponding to approximately 10^{10} cycles.

An American National Standard has been written to address piping vibration. The standard is ANSI/ASME OM3-1982, "Requirements for Preoperational and Initial Startup Vibration Testing of Nuclear Power Plant Piping Systems" (herein referred to as OM3).* The screening methods discussed in this paper are included in this standard. To avoid fatigue failures, this standard limits the maximum calculated alternating stress intensity, S_{alt}, as follows:

$$S_{alt^*} = \frac{M}{Z} C_2 K_2 F_s \leqslant \alpha S_{el} \quad (\alpha S_{el} / F_s = 7{,}690 \text{ psi for carbon steel}) \qquad (1)$$

where: C_2 = secondary stress index as defined in the ASME Code [4]

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*Modifications planned for Rev. 1 of OM3 are included in eq.(1).

K_2 = local stress index as defined in the ASME Code

M = maximum zero to peak dynamic moment loading due to vibration only

S_{el} = alternating stress (S_a) at 10^6 cycles from Figures I-9.1 or I-9.2 of Section III of the ASME Code

Z = section modulus of pipe

α = 0.8 or 0.6 for materials covered by Figure I-9.1 or I-9.2, respectively, of Section III of the ASME Code

F_s = a factor of safety of 1.3. Where the user demonstrates analytically or by experience that the screening methods used are inherently conservative by at least a factor of 1.3, then this factor of safety need not be included in the calculation of S_{alt}.

2.1 Simple Beam Models

Vibratory motion can be described in terms of displacement, velocity or acceleration. Likewise acceptance criteria can be specified in terms of any three of these parameters. Figure 1 illustrates the simple beam models that were used to calculate screening displacement limits in a recently completed piping vibration monitoring program at a nuclear power plant. [5] Only two types of models were used to determine initial screening vibration limits. These models were a fixed-fixed beam and a fixed-guided beam.

The fundamental vibrational mode for a fixed-fixed beam is used to calculate the deflection limits. Combining the maximum deflection and moment equations resulting from the fundamental mode shape, together with the allowable stress intensity (eq. 1), the maximum allowable peak-to-peak deflection, Δ, can then be expressed as follows:

$$\Delta = 0.006 \frac{L^2}{D_o C_2 K_2 F_s} \qquad (2)$$

where: L^2 = characteristic span length, ft (see Fig 1)

D_o = pipe outside diameter, in.

Note that the fundamental shape of a fixed-guided beam is identical to that of a fixed-fixed beam from a fixed point to the center. Therefore, by using L/2 in eq. 2, the maximum allowable peak-to-peak deflection for a fixed-guided beam becomes:

$$\Delta = 0.024 \frac{L^2}{D_o C_2 K_2 F_s} \qquad (3)$$

Allowable vibration displacements based on eq. 2 and eq. 3, assuming a peak stress index (C_2K_2) equal to 5.0, are shown graphically in Figure 2.

These simple beam models were used in a procedure that required the piping system to be walked down during its various operating modes. The actual vibratory response of the piping was witnessed. Based on the actual response of the system, the inspectors decided which simple beam model to use and then determined the characteristic span length (Figure 1). The peak stress indices used in the displacement limit equations (eq. 2 or eq. 3) were equal to the highest indices calculated for all the piping components in the vicinity of the vibrating segment of piping. The characteristic span was determined by locating the vibratory node points (point of zero deflection) adjacent to the measured deflection. If node points could not be determined, then the characteristic span was equal to the distance to the closest seismically rigid restraints. Alternatively, a span length judged to be conservative by the inspectors was used in the deflection limit equations.

2.2 Velocity Criteria

Velocity limits have also been used as criteria for assessing the severity of piping vibrations. The relationship for sinusoidal motion, eq. 4, is used to develop velocity allowables, where $V = \omega d$ (4), V = velocity, where ω = angular frequency of vibrational mode, and d = zero to peak displacement.

The concept of breaking a piping system into a series of small pipe spans and using simple beam analogies to model the vibrating segments of piping is also used to develop the velocity acceptance criteria. By combining the equations for fundamental mode frequency and allowable fundamental mode displacement, it can be shown that allowable velocity is dependent on a constant value times a configuration factor and a factor for lumped masses. [1,6]

2.3 Human Perception and Judgement

Human perception and judgement are key elements in the use of the simplified qualification technique. Typically, vibration measurements are not taken along the entire length of the piping system. The inspector determines where to take measurements and decides on the beam model and characteristic span length to be used. Figure 3 gives examples of allowable vibration limits for various structures and piping. As noted from the figure, vibration levels below the allowable limits will be perceived as being excessive. This indicates that using human judgement to determine what measurements to take is a viable approach.

3. Conservatism of Simple Beam Analogies

Using simple beam analogies to model a vibrating segment of pipe assumes that the characteristic span of the vibrating segment is deflected in a shape similar to the fundamental vibration mode of a simple beam. The use of a fixed-fixed or fixed-guided beam analogy produces the most severe deflected shape. For example, if a fixed-fixed beam were used to model the vibrating spans shown in Figure 4, the resulting allowable displacement limits would be conservative by a factor of 2.0 for span 1 and a factor of 3.3 for spans 2 and 3. Note that lumped masses do affect the deflected shape. For masses near the center span the effect on the simple beam models will be to increase the conservatism. For masses near fixed ends (node points), the effect may be to reduce the conservatism. The examples discussed below include lumped masses (valves).

The simple beam analogies also assume that the location of the peak stress index will coincide with the location of the maximum moment. The ASME Code peak stress index, C_2K_2, may also be conservative. [7] Using only a fixed-fixed or a fixed-guided model also ignores the additional flexibility resulting from a bend in a pipe span. Based on the models given in OM3, ignoring bends can be conservative by as much as a factor of 2.0.

Implementing this criterion requires that the actual response and deflected shape of the vibrating piping be witnessed. The characteristic span is then determined by the location of the vibratory node points. However, in practice it is often not possible to locate node points. In this case the characteristic span length is determined based on the location of adjacent seismically rigid restraints or a conservative span length is determined by the judgement of the inspectors. Using a span length shorter than the actual characteristic span length will result in additional conservatism. Note that a frequency check can be done to verify the conservatism of the simple beam model used. A frequency check involves calculating the frequency of the simple beam analogy and comparing it to the measured frequency of the vibrating piping segment. If the calculated frequency is higher than the measured frequency, then the beam model used is stiffer than the vibrating piping segment and the calculated deflection limits should be conservative.

3.1 Finite Element Model

To analytically assess the conservatism of the simple beam analogies, a sample piping system was modeled as a three-dimensional space frame and a finite element program (PIPSYS [8]) was used to perform a response spectrum analysis. The sample piping system is a feedwater system inside the primary containment of a boiling water reactor.

Three sample cases were examined. The first two cases look at a single mode of vibration. The third case looks at a combination of ten modes of vibration ranging in frequency from 14.9 hertz to 39.0 hertz. The ten modes were pseudostatistically combined using the square root of the double sum method. [9] The deflected shape of the piping resulting from the statistical combination of the ten modes was used in the sample labeled SRDS.

The piping system was then divided into vibrating spans and the simple beam analogies were used to calculate allowable deflection limits for each of these spans. Using the results of the finite element analysis, the stress in each span was then normalized to the allowable stress of eq. 1. A comparison factor, similar to that defined by Stoneking and Kryter [10], was calculated for each span as follows:

$$F_d = \frac{\text{Finite Element Span Maximum Displacement Corresponding to 7,690 psi}}{\text{Simple Beam Analogy Allowable Displacement}} \qquad (4)$$

In addition, an F_d' was calculated. This comparison factor assumed that all of the peak stress indices, C_2K_2, were equal to 1.0. Therefore, by comparing F_d and F_d', the effect of the assumption that the peak stress index occurs at the maximum moment location can be quantified.

To assess the validity of the velocity allowable given in OM3, velocity comparison factors, F_v and F_v' (with $C_2K_2 = 1.0$), were calculated as follows:

$$F_v = \frac{\text{Finite Element Span Maximum Velocity Corresponding to 7,690 psi}}{\text{OM3 allowable velocity}} \qquad (5)$$

where the span maximum velocity equals the span maximum displacement multiplied by the modal frequency, ω.

The following equation is used to calculate the OM3 allowable velocity:

$$V_{all} = \frac{C_1 C_4}{C_3} \quad \frac{3.64 \times 10^{-3} \; (\alpha \; S_{el})}{C_2 K_2 F_s} \tag{6}$$

where: C_1 = concentrated weight correction factor
C_3 = pipe content and insulation correction factor
C_4 = pipe configuration correction factor
(other terms are previously defined)

3.2 Case Studies

Two examples taken from piping systems measured during the completion of a piping vibration program at a nuclear power plant are also presented. Only a portion of the actual piping systems was coded and analyzed by the finite element program. The portion analyzed was the section of piping in the vicinity of the vibrating piping segment. This allowed comparison factors to be calculated for that particular segment of piping. The two case studies are for a portion of the Service Water (WS) and a portion of the High Pressure Core Spray (HP) minimum flow line.

3.3 Results

The deflected vibrational shapes used as examples for the FW piping are illustrated in Figures 5, 6, and 7. The first mode vibrational shapes for the WS and HP case studies are shown in Figures 8 and 9. The results of the comparisons are given in Table I. In summary, the displacement allowables calculated via the simple beam analogies were shown to be always conservative. Considering the peak stress indices the F_d' values ranged from 1.5 to 1.7, with an average value of 5.8. (For 18 case studies not detailed in this paper, taken from the piping vibration program at a nuclear plant, the average F_d value was 3.5, and the minimum F_d value was 1.6.) When peak stress indices were not considered, the F_d' values ranged from 1.4 to 7.5, with an average value of 3.3. Comparing F_d and F_d' values indicates that assuming the peak stress index occurs at the maximum moment location can result in significant additional conservatism.

For most cases the velocity allowables as calculated according to OM3 were also shown to be conservative. However, the velocity allowable proved to be unconservative for the HP case study. Considering peak stress indices, the comparison factor F_v ranged from 0.5 to 4.5, with an average value of 2.0 . Considering all peak stress indices to be equal to 1.0, the comparison factor F_v' ranged from 0.5 to 2.1, with an average value of 1.2. Based on these comparisons additional work is required to develop a velocity criterion that will consistently result in conservative allowables. For example, for the vibrating spans shown in Figure 4, F_v' is equal to 1.5 for spans 2 and 3, but F_v' is equal to 0.9 (unconservative) for span 1 (assuming $C_1 = 1.0$, $C_3 = 1.0$, $C_4 = 0.7$). Whereas the F_d' values were equal to 3.3 and 2.0. To develop a more usable velocity criterion, the pipe configuration correction factor, C_4, should be further developed to better account for the mass and stiffness effects that more complex piping configurations have on the frequency assumptions of this criterion.

These results indicating that the displacement criterion is conservative and the velocity criterion is sometimes unconservative agree with the results of a study completed by Stoneking and Kryter. [10] Note that the OM3 velocity screening allowable of 0.5 in./sec represents a conservative value. [6]

4. Conclusions

Velocity acceptance criteria hold some promise as usable screening tools for piping vibrations. However, the effects that complex piping configurations have on the frequency assumptions must be better accounted for. The drawback with such criteria is that the use of complicated correction factors will make the velocity method more difficult to implement.

The two simple beam analogies addressed in this paper were shown to be always conservative by at least a factor of 1.5. In addition, the use of these two models generally did not result in excessively conservative allowables. Using inspectors to monitor piping vibrational response and using the simple beam analogies to calculate allowable displacement limits results in a qualification technique that is easy to implement and will be effective in avoiding vibration-related failures.

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TABLE I: SUMMARY OF COMPARISONS

EXAMPLE	NODE POINTS DEFINING CHARACTERISTIC SPAN	SIMPLE BEAM ANALOGY*	ALLOWABLE DISPLACEMENT IN MILS PEAK TO PEAK		COMPARISON FACTORS				NOTES
			FINITE ELEMENT	BEAM ANALOGY	F_d	F_d'	F_v	F_v'	
FW	4-2	Fx-Fx	δ_1 = 142	28	5.1	4.2	1.4	1.2	1,2,5
Mode 2	3-4	Fx-Fx	δ_2 = 148	50	3.0	2.9	1.4	1.4	3,6
(15.9 hertz)	5-6	Fx-Fx	δ_3 = 398	46	8.7	4.0	3.0	1.4	4,7
	7-8	Fx-Fx	δ_4 = 104	36	3.0	2.8	1.2	1.0	4,11
	9	Fx-Gd	δ_5 = 184	20	9.0	4.9	1.4	0.8	4,7
FW	1-2	Fx-Fx	δ_6 = 82	54	1.5	1.5	1.1	1.0	4,6
Mode 6	4	Fx-Gd	δ_7 = 130	38	3.5	2.2	1.4	0.9	4,7
(24 hertz)	2-3	Fx-Fx	δ_8 = 130	26	5.1	2.5	2.0	1.0	1,2,3,5
	5-6	Fx-Fx	δ_9 = 286	38	7.5	2.1	3.2	0.9	4,7
FW	2	Fx-Gd	δ_{10} = 246	38	6.5	3.7	---	---	4
SRDS	4	Fx-Gd	δ_{11} = 124	84	1.5	1.4	---	---	1,2,3
	5-6	Fx-Fx	δ_{12} = 626	40	15.7	4.5	---	---	4
	7-8	Fx-Fx	δ_{13} = 76	50	1.5	1.5	---	---	4
WS Mode 1 (4.5 hertz)	1	Fx-Gd	δ_1 = 164	20	8.2	7.5	2.4	2.1	1,2,3,8
WS SRDS	1	Fx-Gd	δ_2 = 162	20	8.1	7.1	---	---	8
HP Mode 1	1-2	Fx-Fx	δ_4 = 28	12	2.3	2.4	0.5	0.5	1,2,9
(16.4 hertz)	3-1	Fx-Fx	δ_5 = 422	40	10.6	3.3	4.5	1.4	3,10
HP	1-2	Fx-Fx	δ_6 = 36	12	3.0	2.0	---	---	9
SRDS	3-1	Fx-Fx	δ_7 = 400	40	10.0	3.0	---	---	3,10
HP STRAIN GAUGE	1-2	Fx-Fx	δ_8 = 33	12	2.7	---	---	---	

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*Fx-Fx = Fixed-fixed
Fx-Gd = Fixed-guided

NOTES

1. Span with highest stress without considering peak stress indices (C_2K_2)
2. Span with highest stress considering peak stress indices (C_2K_2)
3. Span with largest displacement
4. Span with intermediate stress and displacement
5. Velocity correction factors: $C_1 = 0.7$, $C_3 = 1.16$, $C_4 = 1.0$, maximum peak stress index = $C_2K_2 = 3.39$
6. Velocity correction factors: $C_1 = 0.7$, $C_3 = 1.16$, $C_4 = 1.0$, maximum peak stress index = $C_2K_2 = 3.00$
7. Velocity correction factors: $C_1 = 1.0$, $C_3 = 1.21$, $C_4 = 1.0$, maximum peak stress index = $C_2K_2 = 3.43$
8. Velocity correction factors: $C_1 = 0.8$, $C_3 = 1.46$, $C_4 = 1.0$, maximum peak stress index = $C_2K_2 = 15.86$
9. Velocity correction factors: $C_1 = 1.0$, $C_3 = 1.29$, $C_4 = 1.0$, maximum peak stress index = $C_2K_2 = 6.95$
10. Velocity correction factors: $C_1 = 1.0$, $C_3 = 1.29$, $C_4 = 1.0$, maximum peak stress index = $C_2K_2 = 4.54$
11. Velocity correction factors: $C_1 = 1.0$, $C_3 = 1.21$, $C_4 = 0.7$, maximum peak stress index = $C_2K_2 = 3.43$

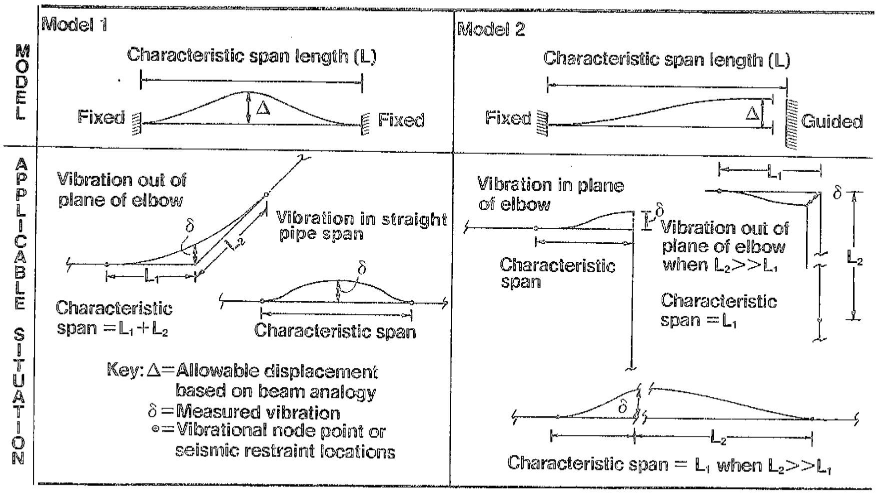
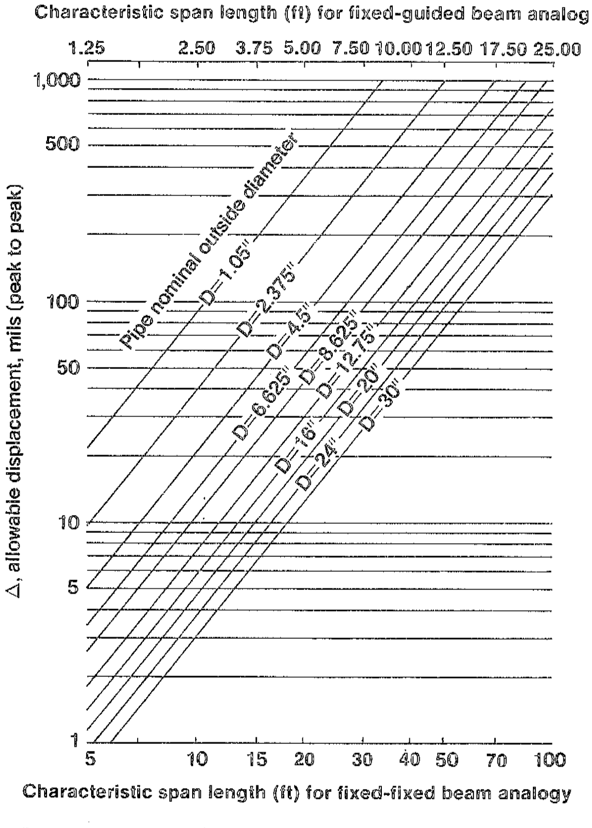
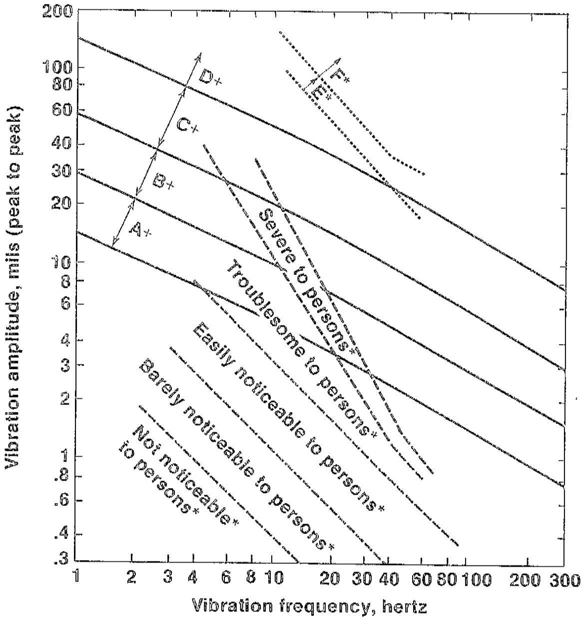


Figure 1 Simple Beam Analogies



Peak stress index ($C_2 K_2$) assumed equal to 5.0

Figure 2
Screening Allowable Displacement Limits for Piping Steady-State Vibration



* Richart [11] + Wachel [1]

A	Design piping vibration level
B	Marginal piping vibration level
C	Correction piping vibration level
D	Danger piping vibration level
E	Caution to structures (due to blasting)
F	Danger to structures (due to blasting)

Caution: Indicated vibration limits are for average piping systems constructed in accordance with good engineering practices. Make additional allowances for critical applications, unreinforced branch connections, etc. Limits are based on experience. The values may be unconservative or overly conservative for some configurations.

Figure 3
Sample Allowable Vibration Levels

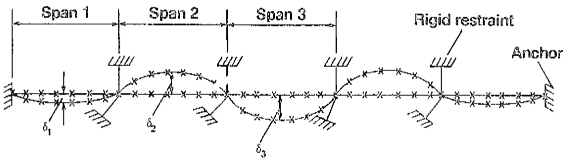


Figure 4 Multiple Support Span

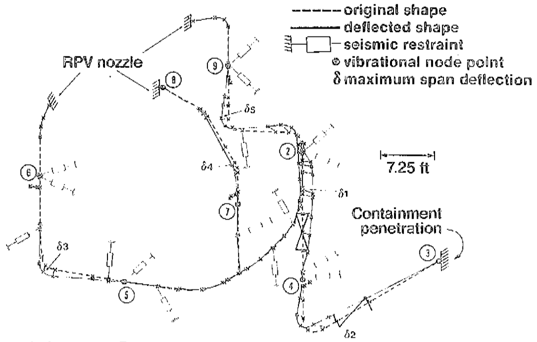


Figure 5
Feedwater Piping, Isometric, Second Mode, Deflected Shape

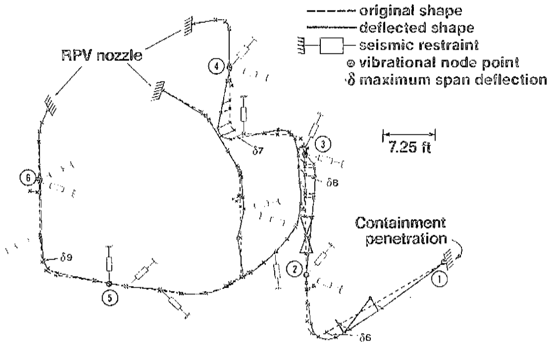


Figure 6
Feedwater Piping, Isometric, Sixth Mode, Deflected Shape

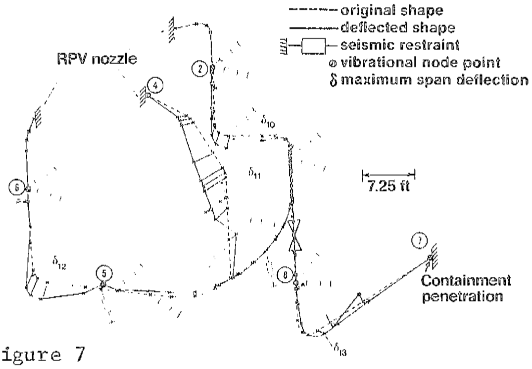


Figure 7
Feedwater Piping, Isometric, SRDS, Deflected Shape

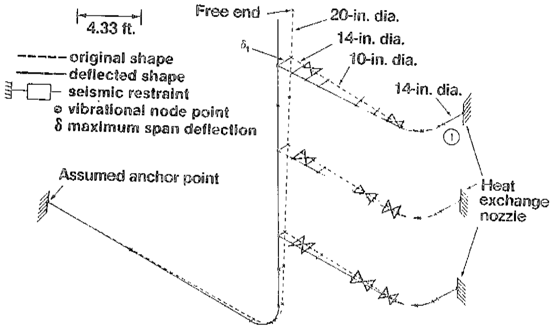


Figure 8
First Mode of WS Piping Segment

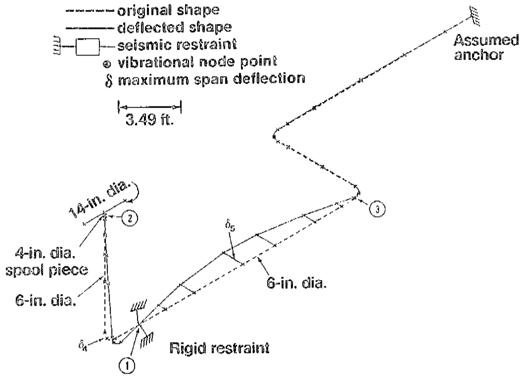


Figure 9
First Mode of HP Piping Segment