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Further development of a static seismic analysis method for piping systems: the load coefficient method

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ABSTRACT: This paper presents recent efforts toward development of a simplified static seismic analysis method for piping systems. The recent development of this technique commonly called the Load Coefficient Method has focused on two approaches. The first approach uses as input the site ground response spectra and the second approach uses as input the amplified or floor response spectra. This latter approach is currently under consideration for incorporation into Appendix N of Section III Division 1 of the ASME Boiler and Pressure Vessel Code. The results of the both approaches have been compared to the Response Spectrum Modal Analysis Method and found to be conservative. Both approaches are presented in this paper with an emphasis on the second approach. In additional the benchmark analysis which serve as a basis for the method are overviewed and an explanation of the use of the method is also presented.

NOMENCLATURE:

A = The zero period ground acceleration, ZPGA (g)
A_c = Amplification coefficient depending on the potential resonance between the piping and the structure developed on a plant specific basis
a_{vh} = Total acceleration applied to the inline component extended structure center of gravity (cg) in the horizontal direction (g)
a_{vv} = total acceleration applied to the inline component extended structure center of gravity (cg) in the vertical direction (g)
A_{xv} = The amplification factor at level x related to the variation of response as a function of building height
$A_{xv} = 1.0 + 1.5(h_{xv}/h_{nv})$ of $V_s > 3500$ ft/sec
$A_{xv} = 1.5 + 1.0(h_{xv}/h_{nv})$ if $V_s \leq 3500$ ft/sec
A_{xh} = The amplification factor at the piping support elevation as a result of torsional motion about a vertical axis through the Center of Shear of the building at that elevation
$A_{xh} = 1.0 + 0.3(h_{xh}/h_{nh})$ for Unsymmetric Structures
$A_{xh} = 1.0 + 0.15\ (h_{xh}/h_{nh})$ for Symmetric Structures
d_m = 1.2 for pipe moments; 1.0 for support loads
h = height from the pipe centerline to inline component extended structure center of gravity (cg)(ft)
h_{nh} = The maximum horizontal distance from the Center of Shear of the building to the building edge at the component support elevation (ft)
h_{nv} = The overall height of the building (ft)
h_{xv} = The height above the base to level x (ft)
h_{xh} = The horizontal distance of the component from the center of shear of the building at the component support elevation (ft)
I_v = Second moment mass of the valve extended structure about the piping centerline
K = $d_m * K_1$
K_1 = A factor which accounts for the shape of the applicable design ground spectra and amplification of the floor response spectra
K'_{hi} = The acceleration coefficient applied to the inline component extended structure center of gravity (cg) acceleration in the ith horizontal direction
K'_v = The acceleration coefficient applied to the inline component extended structure center

of gravity (cg) acceleration in the vertical direction
l_{hi} = Horizontal span in the ith direction between lateral supports measured along the axis of the pipe. Lateral supports added to the piping system specifically to support large inline components such as valves, flanges, etc., do not need to be considered in the determination of 1_{hi} value
l_v = Deadweight vertical support span from Table NF 3611.1 for the nominal pipe size for the piping system under consideration
P_D = Design pressure (psig)
P_o = Operating pressure (psig)
R = Higher mode and deformed shape participation factors: for pipe supported at one or two points R = 1.0; for pipe supported at more than two points R = 1.5
R_{AMIN} = Minimum axial seismic support design load (lbf)
R_{LMIN} = Minimum lateral seismic support design load (lbf)
R_{VMIN} = Minimum vertical seismic support design load (lbf)
S_{ami} = Peak acceleration of applicable amplified or floor response spectra in the ith direction (in g's)
S_{avent} = Peak acceleration of applicable amplified or floor response spectra in the vertical direction (in g's)
V_s = shear wave velocity of the foundation media (ft/sec)
W = The total piping deadload which exists during the postulated seismic event
W′ = Piping weight per unit length in lbf/ft
W_v = Weight of the inline component extended structure considered at its center of gravity (cg) location (lbf)

1 INTRODUCTION

This paper presents recent developments in simplified static seismic analysis methods for piping systems. This methodology has evolved over more than a decade first as ASME Code Case N- 468 and currently this approach is proposed for incorporation in Appendix N of the American Society of Mechanical Engineers (ASME), Boiler and Pressure Vessel Code (BPVC) Section III, Division 1. [1]

The primary purpose of this method, commonly referred to as the Static Load Coefficient Method (LCM) is to provide a rational extension of the Equivalent Static Analysis Method (ESAM) given in the USNRC Standard Review Plan (SRP) Section 3.7 [2] for the static seismic analysis of piping systems. The ESAM allows that static seismic analysis may be performed by applying an acceleration factor times the piping distributed and lumped mass of 1.5 times the peak acceleration valve given in the applicable amplified response spectra. In most cases the ESAM results in extremely conservative analysis which over predicts the seismic piping stresses, support loads, displacements, and accelerations. The LCM provides a static seismic analysis procedure which may be performed by applying an acceleration factor to piping distributed and lumped mass which is significantly less than the 1.5 factor required by the ESAM. As a further benefit the LCM does not require any control of piping support stiffness or deflections, thereby having the potential to significantly reduce the size and cost of nuclear piping supports by a factor of 2 to 5.

2 BACKGROUND

The recent developments of the LCM focused on two primary approaches. The first approach developed Load Coefficients which were applied to the plant site Zero Period Ground Acceleration, ZPGA. Two separate methodologies were developed to apply this approach. The second approach was the development of generic simplified coefficients to be applied to peak accelerations of the applicable amplified floor response spectra. It is this second approach that is currently under consideration for incorporation into Appendix N of Section III of the ASME Boiler and Pressure Vessel Code. This manuscript presents a general overview and some background on the first approach but focuses on the latter approach. More detailed in depth discussions of the technical basis and history of the Load Coefficient Method is presented by Stevenson [3], Stevenson, Thomas and Masopust [4], Zhao and Stevenson [5], and Adams and Stevenson [6]. Examples of the application of the LCM are presented by Antaki [7], Aggarwal and Vanvat [8], and Caldwell and Willis [9].

3 OVERVIEW OF APPLICATION OF THE LCM

The basic tenant of the LCM is that with certain caveats the results of the Dynamic Response Spectra

Modal Analysis Method, (RSMAM) applied to a piping system can be enveloped by applying a factor times the horizontal and vertical values of the Zero Period Ground Acceleration (ZPGA), or peak accelerations of the amplified or floor response spectra applicable to the analysis of the subject piping system.

The seismic analysis is performed by applying a static loading to piping system distributed and concentrated mass individually in each of two orthogonal horizontal directions and one vertical direction to determine the resulting bending and torsional moments in the piping, piping displacements and applied support loads. The results for each of these three individual runs are then combined on a square root of sum of the squares (SRSS) basis to determine the maximum pipe loadings, stresses, displacements and applied support loads.

The seismic forces determined by the LCM consider only the applied seismic inertia loadings. As is also the case with the RSMAM the effects of Seismic Anchor Motions must be evaluated separately using appropriate methods. In the LCM piping analysis, supports are assumed to be points of zero displacement. In comparison with dynamic analysis this assumption will tend to over estimate the real frequency of the piping system. This higher frequency result will conservatively shift the response toward the peak of the floor spectra for all support spacings where seismic stresses are a design concern. Therefore, the application of the LCM does not require the use of actual support stiffnesses nor the specification of a limiting support deflection criteria.

4 METHODOLOGY OF VERIFICATION OF THE LCM

Both the LCM approaches are developed and verified on a statistical basis by studying and evaluating the results and controlling parameters of over 2700 individual piping analysis. The results reviewed are:

1. the ratio of piping stresses predicted by the LCM to those predicted by the RSMAM
2. the ratio of piping support loads predicted by the LCM to those predicted by the RSMAM
3. the ratio of the valve accelerations predicted by LCM to those predicted by the RSMAM.

These studies demonstrated that the results of the LCM method envelop the results of the RSMAM with between a (mean - (2σ)) and (mean - (3σ)) confidence level (97% - 99% confidence level).

4.1 Models used in the study

For both methods using the first approach (factor times ZPGA) the verification studies use ten basic geometric models assuming 2″ and 4″ nominal pipe sizes. This resulted in a total of 20 individual analysis models. A summary of the study model parameters is as follows:

1. Piping Size : 2″ ϕ - schedule 40; 4″ ϕ - schedule 40
2. Piping Material : A106B Carbon Steel
3. Piping Weight : 1.1*(weight of water filled piping)
4. Connection types : 2″ ϕ piping - socket welded
5. Internal Pressure : 0-300 psig

The deadweight support spans are assumed to be as specified in ASME BPVC Section III, Subsection NF-3611. For each geometric model seven different lateral spans are used in which the Lateral to Vertical Support Span Ratio (LVSSR) is varied from one to seven times the deadweight span. This combination of geometrics and LVSSR results in 140 unique piping analysis models. For the second approach (factors times amplified response spectra) the verification studies use only the 2″ models as described above.

4.2 Response spectra used in the studies

For the first approach the input response spectra used above 2 hz is the response spectra developed by SSRAP for the SQUG A-46 program [10]. Below 2 hz this spectra is modified to be consistent with a Regulatory Guide 1.60 [11] spectra for a plant on a soft soil site. Three ZPGA levels are considered in the study were .1g, .2g and .3g. The resulting spectra is shown in Figure 1.

In the second approach two response spectra representative of Regulatory Guide 1.60 amplified response spectra found mid height in typical nuclear power plant structures are used in the study. One amplified response spectrum is assumed to be from a structure founded on medium soil (2000 ft/sec $\leq V_s \leq$ 3500 ft/sec) and one spectrum is assumed to be from a structure founded on component rock ($V_s >$ 3500 ft/sec). These amplified spectra used in the study are shown in Figure 2 and Figure 3.

4.3 Analysis methods of the study

The static analyses are run as described in Section 3. The dynamic analysis are run by using the 3-D RSMAM, with modal and directional combinations, including closely spaced modes combined in accordance with Regulatory Guide 1.92 [10]. The "left out force" method is used to account for any non-participating mass.

5 THE FIRST APPROACH

In the first method of this approach the static seismic load, F, applied to the piping is determined by the following relationship:

$$F = A\ R\ A_c\ A_{xh}\ A_{xv}\ W$$

where the constants are defined in the nomenclature and the values of the parameters used in this study are as given in Table 1.

In the second method of this first approach the static seismic load F_{pi} applied to the piping is determined by the following relationship:

$$F_{pi} = K\ A\ W$$
$$K = K_1 d_m$$

where the constants are as defined in the nomenclature and the values of the parameters used in this study are defined in Table 2.

Once the coefficients are established the following analysis cases are run:

1. Static analysis with the applied loads determined based on the parameters given in Table 1 and Table 2 (application of LCM).
2. Static analysis with applied g loads equal to 1.0 times peak acceleration of the response spectra. given in Figure 1.
3. Static analysis with the applied loads equal to 1.5 times the peak acceleration values of the response spectra given in Figure 1.
4. RSMAM with the response spectra given in Figure 1.

This study resulted in significant analysis output and data, the presentation of which is beyond the scope of this paper. This data and information is presented in depth by Stevenson, Thomas and Masopust [2]. However, the general conclusion of this study are:

1. The second method of this approach correlated well with the RSMAM results. K_1 factors of 1.9, 1.6 and 1.3 were used in the analysis and had a limiting value of 2.4 been used in all cases this later approach would have given conservative results compared to the RSMAM.
2. It was determined that the method is applicable to LVSSR of 3 to 7. For smaller LVSSR's a higher load coefficient should be used.
3. The results also indicated that this analysis method could be simplified and applied with greater accuracy for complex commercial nuclear power plant structures if amplified or floor response are used in lieu of the ground spectra with the coefficients being applied to the peak acceleration of the instructure amplified or floor response spectra.

6 THE SECOND APPROACH

Using the results of the study for the first approach it is decided to develop the simplified approach using factors times the peak of the amplified floor response spectra. This section describes that development effort.

6.1 Development of the load coefficients

The first step in this second approach in this process was to run the static analysis for each of the study models with applied acceleration values equal to 1.0 times the peak acceleration of the amplified spectra shown in Figure 2 and 3. Next each model was analyzed using the RSMAM with the same amplified spectra. For piping stress, and for each support loads, the ratio of LCM/RSMAM as a function of the LVSSR was plotted on bar graphs.

Based on reviewing these data tabulations the following relationships are determined for the applied Seismic Forces

$$F_{phi} = K_{hi}\ S_{ami}\ W$$
$$F_{pv} = K_v\ S_{ami}\ W$$

where the values of K_H and K_V are shown in Table 3 and Table 4 and the remaining parameters are given in the nomenclature. It is important to note that the LVSSR shown in Table 3 and Table 4 is the ratio of the actual lateral support spans to these given in Table NF-3611.1 not to the actual vertical supports span.

Once the coefficients are established the following analysis cases are run:

1. Static analysis with the applied loads equal to the Load Coefficients of Table 3 and Table 4 times the peak acceleration of the amplified response spectra. (application of LCM)
2. Static analysis with applied loads equal to 1.0* peak acceleration of the amplified response spectra.
3. Static analysis with the applied loads equal to 1.5* peak acceleration of the amplified response spectra.
4. RSMAM using the amplified response spectra of Figure 2 and Figure 3

The results of these analysis for each model are then tabulated in the following ratios for the maximum piping stresses:

1. LCM/RSMAM
2. (1.0 * Peak Acceleration)/RSMAM
3. (1.5 * Peak Acceleration)/RSMAM

Similar ratios are then made for piping displacements, and for support loads on an individual support by support basis. The resulting ratios from each model are then combined as a function of LVSSR, mean values calculated and the results plotted on minimum, maximum, mean bar graphs. In all cases the pipe stress and displacement values predicted by the RSMAM enveloped those predicted by the LCM. There were a few isolated cases where the ratio of the LCM/RSMAM for support loads was less than one. This occurred for less than 3% of the supports. To provide a higher confidence level in the method it is decided to develop a minimum support factor to address these isolated instances when the LCM did not envelop the RSMAM as described in Section 6.2..

6.2 Support minimum seismic design loads

Minimum support design loads are developed by using the worst case models (the 3 models with supports having the lowest ratio of the LCM/RSMAM) and developing 4″ ϕ, Sch. 40, 8″ ϕ Sch. 40, 16″ ϕ Sch. 40 and 24″ ϕ Sch. 40 piping models. For each of these models (15 total models) two analysis case are run: RSMAM and a static analysis using the load coefficients developed. From these analysis runs for the worst case support, a plot of the ratio of the LCM/RSMAM is developed. The RSMAM loads were taken as the minimum design loads for this piping size. These loads are further modified by normalizing them to the piping weight per unit length and to 1.0 g amplified response spectra peaks. The resulting method to establish the minimum seismic design loads were then provided as follows:

$$R_{LMIN} = (MSLF)(W')[\textstyle\sum^{2}_{i=1} (S_{ami})^2]^{1/2}$$

$$R_{AMIN} = (MSLF)(W')[\textstyle\sum^{2}_{i=1} (S_{ami})^2]^{1/2}$$

$$R_{VMIN} = (MSLF)\,(W')\,S_{avert}$$

where MSLF is determined from the Table 5 and the remaining parameters are defined in the nomenclature.

6.3 Valve acceleration predictions

The final area which had to be addressed for this second approach is the prediction of accelerations on large inline components with extended structures, i.e. mainly valve operators. The critical parameter in evaluating the valve extended structure response contribution is the valve second moment of mass ($I_v = W_v h^2$). Therefore this value, (I_v) is a function of two values W_v and h and for the purposes of this study the following parameter ranges were considered:

W_v : 50 lbf to 550 lbf in 50 lbf increments
h : Valve extended structure dg height 6″ to 48″

The range of parameters envelops any set of inline component extended structure parameters which would be experienced on 2″ piping systems. To generalize this approach the I_v valve is then normalized to the total piping weight unit length (W′). This normalization is chosen because the piping weight per unit length is a function of the cross-sectional metal area as is the piping torsional stiffness. The straight, single span series of piping models are chosen for an initial study. For each model (LVSSR equal to 1 thru 7) valves having the extended structures shown in Table 6 are inserted in the model in the center of the middle span for odd numbered span ratios and in the center of the span adjacent to the middle span for even number span ratios. These valve models included a model of the extended structure which is a rigid connection from the piping centerline to the extended structure cg with a mass lumped at the end of this rigid member. For each piping model, extended structure model, and span ratio a RSMAM was run. This is done for both the rock and soil spectra. This results in a total of 126 analyses cases.

For the RSMAM the accelerations in each of two orthogonal horizontal directions (x,z) and one vertical direction are tabulated. The resulting total horizontal acceleration is determined as the square-root-sum-of-the-squares of the two horizontal orthogonal direction accelerations. The ratios of the peak amplified spectra accelerations to the RSMAM determined accelerations are plotted.

Based on a review of this data the following simplified conservative approach is developed for determining the accelerations on inline component extended structures when using the load coefficient method:

$$a_{vh} = [\textstyle\sum^{2}_{i=1} (K'_{hi}S_{ami})^2]^{1/2}$$

$$a_{vh} = K'_{v}S_{ami}$$

where the K′ values are as shown in Table 7 and Table 8 and the remaining parameters are as defined in the nomenclature.

7 CLOSURE

This paper has presented an overview and recent development efforts for the LCM and the version currently under consideration for incorporation into the ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendix N. The LCM which is empirical has been verified by over 2700 individual analysis cases and has been extensively reviewed over a ten year period by several subcommittees within the ASME Boiler and Pressure Vessel Code hierarchy. The authors wish to acknowledge that funding for a portion of this work was provided by the Design Division of the Pressure Vessel Research Council under Grant 92-02.

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Table 1 - Coefficients Used in the Sample Analysis of the First Method of the First Approach

Coefficient	Value
A	.1, .2, .3
R	1.5
A_o	1.4
A_{xh}	1.15
A_{xv}	1.7

Table 2 - Coefficients Used in the Sample Analysis of the Second Method of the First Approach

Coefficient	Value
A	.1, .2, .3
d_m	1.0, 1.2
κ_1	1.3, 1.6, 1.9

Table 3 - Second Approach Load Coefficients - Rock Spectra

Horizontal		Vertical	
Coefficient	Span Ratio	Coefficient	Span Ratio
1.0	LVSSR < 2.5	1.0	All LVSSR
.6	2.5 ≤ LVSSR ≤ 4.0		
.4	LVSSR > 1.0		

Table 4 - Second Approach Load Coefficients - Soil Spectra

Horizontal		Vertical	
Coefficient	Span Ratio	Coefficient	Span Ratio
1.0	LVSSR < 3.5	.75	LVSSR < 4.0
.65	3.5 ≤ LVSSR ≤ 5.0	1.0	LVSSR ≥ 4.0
.4	LVSSR > 5.0		

Table 5 - Second Approach Minimum Support Load Factors

Nominal Pipe Size, ϕ, (in)	MSLF (ft)
$\phi \le 2''$	8.5
$2'' < \phi \le 4''$	8.0
$4'' < \phi \le 6''$	7.5
$6'' < \phi \le 8''$	7.0
$8'' < \phi \le 12''$	6.5
$\phi > 12''$	6.0

Table 6 - Inline Component Extended Structure Models Used in the Initial Study

W_v (lbf)	h (in)	$W_v{*}h^2/w'$ in^2-ft
100	9	1440
250	9	3610
400	12	10267
300	18	17326
150	30	24064
400	24	41070
500	36	115508
500	42	157219
450	48	184813

Table 7 - Values of K'_{hi}, K'_v for Rock Sites

	$W_v h^2/W' \le 20{,}000$	$W_v h^2/W' > 20{,}000$
$l_{hi} \le 2\ l_v$	$K'_{hi} = .85$ $K'_v = 1.1$	$K'_{hi} = .85$ $K'_v = 1.2$
$l_{hi} > 2\ l_v$	$K'_{hi} = .8$ $K'_v = 1.1$	$K'_{hi} = .9$ $K'_v = 1.2$

Table 8 - Values of K'_{hi}, K'_v for Soil Sites

	$W_v h^2/W' \le 100{,}000$	$W_v h^2/W' > 100{,}000$
$l_{hi} \le 2\ l_v$	$K'_{hi} = .85$ $K'_v = 1$	$K'_{hi} = 1.1$ $K'_v = 1.0$
$l_{hi} > 2\ l_v$	$K'_{hi} = .9$ $K'_v = 1$	$K'_{hi} = 1.0$ $K'_v = 1.25$

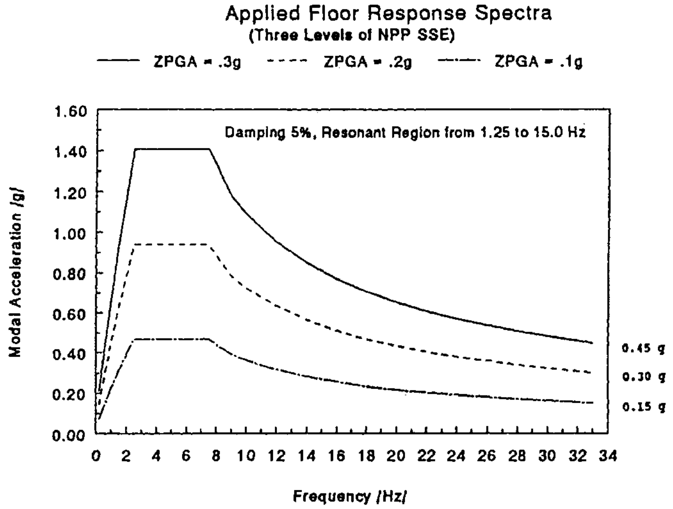

Figure 1 - Response Spectra Used in First Approach Studies

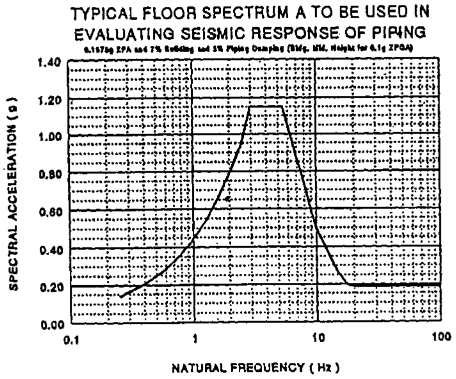

Figure 2 - Soil Founded Response Spectra Used in Second Approach Studies

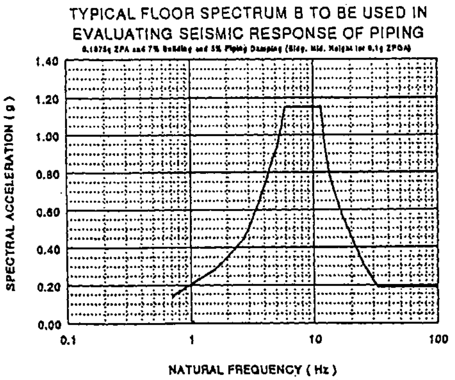

Figure 3 - Rock Founded Response Spectra Used in Second Approach Studies