Comparison Study of Time History and Response Spectrum — Responses for Multiply Supported Piping Systems

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In the past decade, several investigators have studied the problem of independent support excitation of a multiply supported piping system to identify the real need for such an analysis. This approach offers an increase in accuracy at a small increase in computational costs. To assess the method, studies based on the response spectrum approach using independent support motions for each group of commonly connected supports were performed. The results obtained from this approach were compared with the conventional envelope spectrum and time history solutions.

The Response Spectrum Method, whether independent or conventional (i.e., envelope), always requires an additional static analysis in order to include the stresses produced by the differential movements among the support groups. This component of stress does not exist for a piping system supported from a single rigid frame. When the conventional method is used, this analysis is known as a Seismic Anchor Movement (SAM) analysis. One common way of determining the maximum displacement at each support point is from the relationship $S_d = S_a g/\omega^2$, where S_a represents the spectral acceleration in g's at the high frequency end of the spectrum, g is the gravitational constant, and ω is the fundamental frequency of the primary support structure in radians per second. The support displacements are then imposed on the supported item in the most unfavorable combination requiring an engineering judgement. The Independent Time History Method, on the other hand, identifies the inertial component produced by the dynamic effect of the mass points in the piping system and the static component (sometimes known as Pseudo-static Component because of its time dependent characteristic) caused by the phasing between the different support groups. Both these components are time dependent for which the maximum value are of prime interest.

The present study includes a mathematical formulation of the independent support motion analysis method suitable for implementation into an existing all purpose piping code PSAFE2 and a comparison of the solutions for some typical piping system using both Time History and Response Spectrum Methods. The results obtained from the Response Spectrum Methods represent the upper bound solution at most points in the piping system. Similarly, the Seismic Anchor Movement Analysis based on the SRP method over predicts the responses near the support points and under predicts at points away from the supports.

1. Introduction

In the past decade, several investigators have studied the problem of independent support excitation of a multiply supported piping system to identify the real need for such an analysis. Penzien and Clough [1] have presented a matrix formulation for a general lumped mass system. Vashi [2], Wu, Hussain and Liu [3] later implemented this in their piping codes and compared their results with the conventional solutions. Leimbach, Schmid and Sterkel [4,5] also studied this problem and concluded that such an analysis offers an increase in accuracy at a small increase in computational costs. All these studies were based on the Response Spectrum approach using independent support motions for each group of commonly connected supports. The results obtained from this approach were compared with the conventional envelope spectrum and time history solutions.

The Response Spectrum Method, whether independent or conventional (i.e., envelope), always requires an additional static analysis in order to include the stresses produced by the differential movements among the support groups. This component of stress does not exist for a piping system supported from a single rigid frame. When the conventional method is used, this analysis is known as a Seismic Anchor Movement (SAM) Analysis. One common way of determining the maximum displacement at each support point is from the relationship $S_d = S_a g/\omega^2$, where S_a represents the spectral acceleration in g's at the high frequency end of the spectrum, g is the gravitational constant, and ω is the fundamental frequency of the primary support structure in radians per second. The support displacements are then imposed on the supported item in the most unfavorable combination requiring an engineering judgement. The Independent Time History Method, on the other hand, identifies the inertial component produced by the dynamic effect of the mass points in the piping system and the static component (sometimes known as Pseudo-static Component because of its time dependent characteristic) caused by the phasing between the different support groups. Both these components are time dependent for which the maximum value are of prime interest.

In the present study, the dynamic response is obtained by using both the Independent and Uniform Response Spectrum Methods. The former method uses different input support group spectra for each supporting structure whereas the latter method uses the envelope of all the individual group spectra. The individual spectra are correspondent with the acceleration time histories used in the independent time history analysis. The group responses are first calculated for each mode and each direction of excitation. These are then combined component by component via any of the three methods: algebraic, SRSS and absolute sum. After the group combination, the directional and modal combination are performed to obtain the maximum dynamic response of the system. These three group combination results are then compared with the Uniform Response Spectrum as well as the Independent Time History results.

The static responses, on the other hand, are calculated using static analysis methods. The peak displacements of the support points are first obtained from a time history evaluation of the support structure using the input earthquake excitations. Since the phasing between the support points are lost in determining the peak displacements, a phasing is assumed intuitively to represent the worst possible stress condition in the piping system. In the present analysis, the support displacements in each spatial direction are applied independently in this worst possible phase combination and the corresponding responses are combined using either of the three methods: algebraic, SRSS and absolute sum. The final piping responses are compared with the Independent Time History solutions.

For comparison purposes, the resultant moment responses at each piping model point is considered to be the parameter representing the stress intensities. These moment results are displayed in graphs against the nodal location of the piping system.

2. Independent Support Motion Analysis

This study includes a mathematical formulation of the independent support motion analysis method suitable for implementation into an existing all purpose piping code PSAFE2 and a comparison of the solutions for a sample problem using the different methods. The detailed analytical derivatives of the governing equations of motion are given in the report [6] by the authors. The final form of these equations in matrix form is:

For the dynamic response (i.e., inertia effect)

$$M\ddot{X}_D + C\dot{X}_D + KX_D = M\,K^{-1}\,K_{AB}\,\ddot{Z} \quad (1)$$

and for the static response (i.e., Pseudo-static)

$$X_S = -K^{-1}\,K_{AB}\,Z \quad (2)$$

where M, C and K represent the mass matrix, the damping matrix and the stiffness matrix respectively of a piping system, K_{AB} denotes the coupling term between the piping and boundary points, and $\ddot{Z}$ is the ground acceleration time history of the support points. The ground displacement Z is obtained by integrating twice the input acceleration time history using a suitable integration scheme. X_D and X_S define the dynamic and static responses respectively of a piping point when subject to independent ground motion. The absolute response of any point can be calculated by combining these two components of response. It should be noted that both components are time-dependent. The Independent Response Spectrum analysis requires further simplification of eq. (1) similar to the conventional approach and the solution is accomplished by modifying the modal participation factors.

3. Piping Analysis and Results

A comparison of the analysis of simple piping systems with two and three distinct support groups using the Independent Time History Method, Independent Response Spectrum Method and the Conventional Envelope Spectrum Method was performed. In addition, static analyses were performed with the support motion calculated as described above. The input time histories and the response spectra obtained correspond to real earthquake records. The responses from all the support groups were combined algebraically for Independent Time History Method.

The typical piping systems, shown in Figs. 1 and 2, were chosen for the study. Problem number 1 (Fig. 1) has two distinct groups of supports while problem number 2 has three groups. In the independent analysis each support group was subjected to uncorrelated earthquake motions. The same damping value is used for both time history and response spectrum analyses. Each input spectrum was developed from the corresponding earthquake time history and was broadened before use. The envelope spectra used in the uniform response spectrum analyses was the envelope of the unbroadened individual spectra, broadened before use.

After selecting the piping systems and the input loading functions, the three sets of dynamic analyses, mentioned earlier, were performed. They consist of independent time history, independent response spectrum and uniform response spectrum analysis. In each case, the resultant moment response of each piping node was stored for comparison purpose. These results are plotted in Figs. 3 and 5 corresponding to piping systems 1 and 2 respectively.

Each figure consists of five curves each representing the results of one dynamic analysis. Curve 1 represents the lower bound solution and corresponds to the Independent Time

History Method. The Uniform Response Spectrum Method is represented by curve 2 and is not necessarily the most conservative result. Curves 3, 4 and 5 correspond to the Independent Response Spectrum Method where the group contributions were combined by the algebraic, SRSS and absolute sum methods respectively. It is evident that the Absolute Combination Method always yields the upper bound solutions.

As mentioned earlier, the static response components were obtained as a result of a number of static analyses with support movement phasing chosen intuitively. For problem 1 only one phasing choice, out of phase, was used since this problem only has two groups and the out of phase assumption yields the worst stress condition. These results are shown in Fig. 4. On the other hand, the second piping problem, consisting of three groups, could have three distinct modes of phasing which will yield different stress conditions. Out of these one mode representing all groups in phase is presumed to yield the lowest stress resultants in the piping system. Therefore, only the other two possible modes were considered in this study. In each case two groups are out of phase with the third group. These two sets of results are shown in Figs. 6 and 7.

Each of the Figs. 4, 6 and 7 consists of four different curves. Similar to the dynamic component results, curve 1 represents the independent time history solution. The remaining three curves correspond to the three possible combination methods between the three responses caused by imposing support displacements in each spatial direction at a time. Thus curves 2, 3 and 4 correspond to the algebraic, SRSS and absolute summation of the three spatial contributions respectively. Figure 6 shows the results for one phasing assumption while Fig. 7 shows the results for the other phasing assumption.

Figure 4 shows the results for the two group problem with the time history solution, curve 1, representing the lower bound at every point in the piping system. The SAM analysis with absolute sum between the directions is the upper bound solution. This was expected to be the case. On the other hand, Figs. 6 and 7 for the three group problem do not indicate the same trend over the entire region of the piping system.

4. Conclusions

Both the dynamic and static components evaluated in the present study indicate that the independent time history solution yields the lower bound response for almost all the points in a typical piping system. However, for some points the simplified analytical procedures, Response Spectrum Methods coupled with Seismic Anchor Movement Methods, under predict these responses. In order to fully qualify the above observations, additional piping systems with different loading functions must be studied.

The Uniform Response Spectrum Method using the envelope spectrum does not necessarily predict the most conservative dynamic response. This occurs because although the input acceleration levels may be larger than they should be, support groups are implicity combined as if they are in phase, a potentially unconservative phasing assumption. Several other cases, not included in this paper, have revealed that the Uniform Response Spectrum Method predicts lower responses as compared to the Independent Response Spectrum Methods if a strong phase relation exists between the modal participation factors predicted for each group. A program is underway to study the Independent Response Spectrum Method and the group combination methods to account for the phasing between groups in a conservative fashion.

As regards the Seismic Anchor Movement analysis, the static analysis was found to over predict the response at certain locations, specifically at the support points with moment restraint, and under predicts responses at points away from such supports. Since the SAM analysis method used herein is just one of many methods that could be employed, these characteristics should not be inferred to apply to SAM methods in general. The SAM method used can be considered to be one of the methods used in industry. This method becomes obsolete as the number of groups is increased beyond three or four. Future studies to develop a particular SAM methodology to provide response predictions which better approximate time history results are being pursued by the authors.

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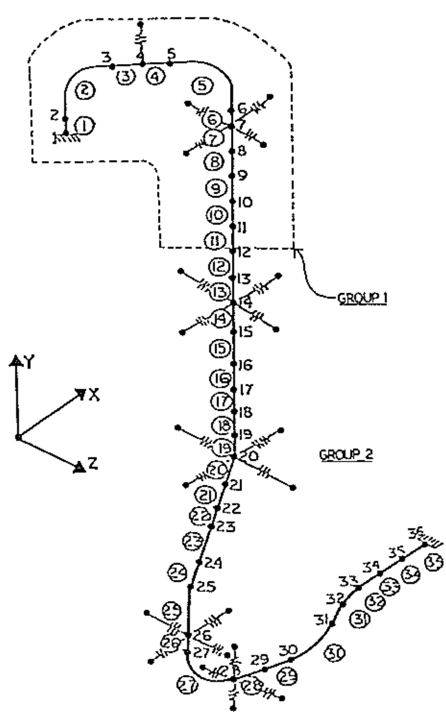

Figure 1 - Piping Problem No. 1

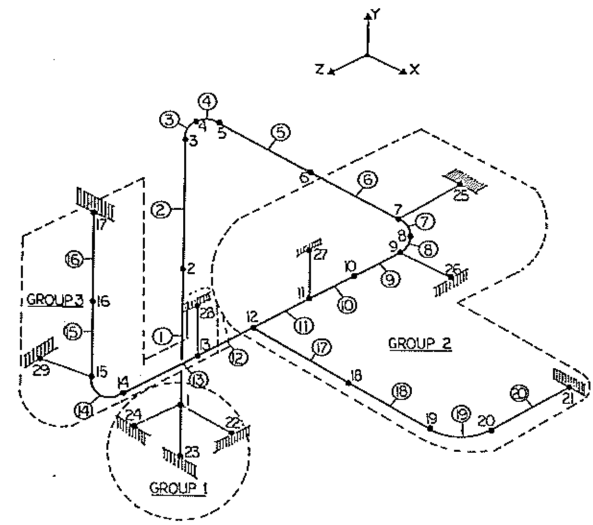

Figure 2 - Piping Problem No. 2

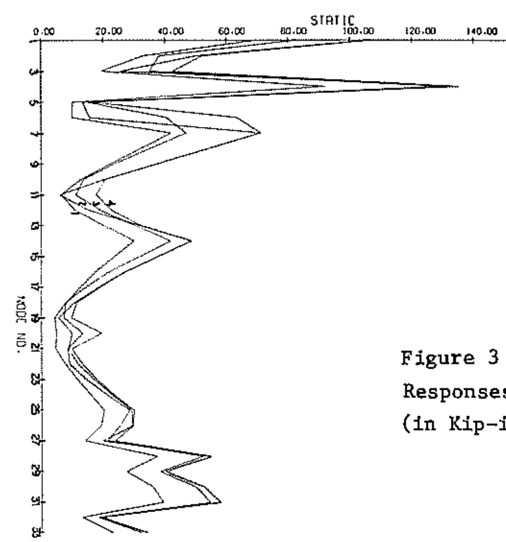

Figure 3 - Dynamic Resultant Moment Responses of the Piping System 1 (in Kip-inch)

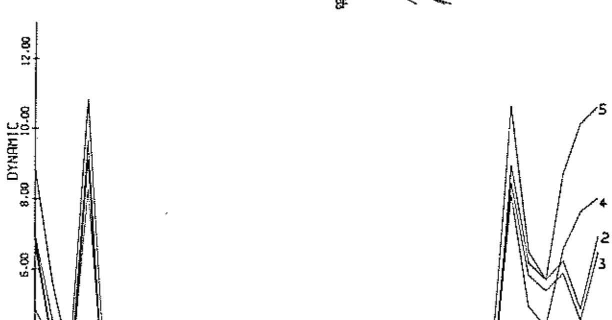

Figure 4 - Static Resultant Moment Responses of the Piping System 1 (in Kip-inch)

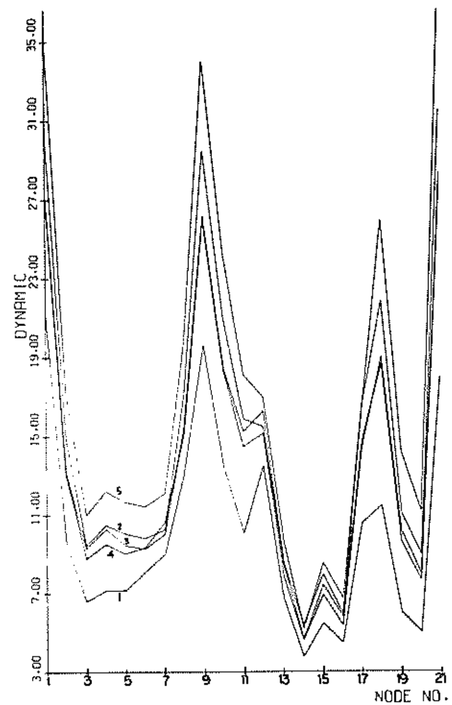

Figure 5 - Dynamic Resultant Moment Responses of the Piping System 2 (in Kip-inch)

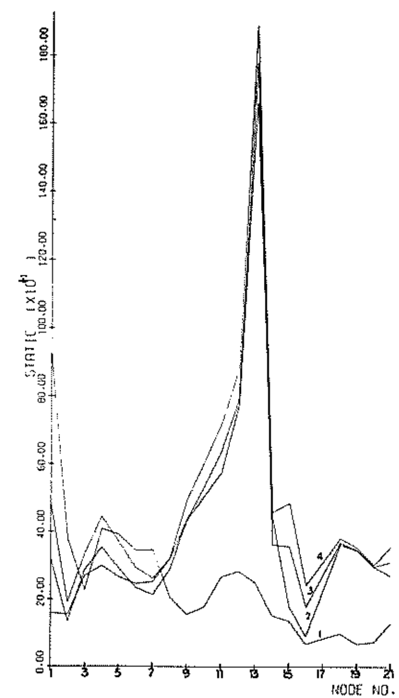

Figure 6 - Static Case 1 Resultant Moment Responses of the Piping System 2 (in Kip-inch)

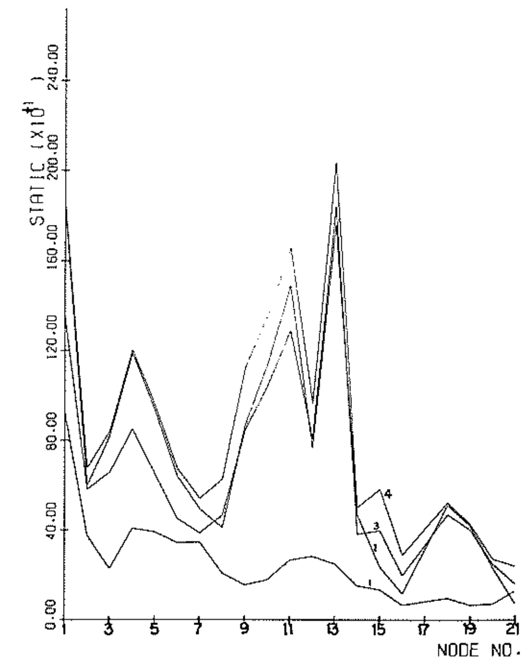

Figure 7 - Static Case 2 Resultant Moment Responses of the Piping System 2 (in Kip-inch)