Novel Developments in Linear Modal Description of Piping System Dynamic Behavior

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INTRODUCTION

Novel developments in dynamic analysis of piping systems are described below. The ASME BPV Codes, 1986 describes methods that are considered as adequate to analyze piping systems under dynamic loading, and also states that the method described in the codes are not the only acceptable ones. With straightforward application of the principles and methods laid down in the code novel numerical techniques can be developed. These techniques allow to obtain correct, conservative estimates of the piping system response and to reduce the computed stresses the same time. Beyond that, the particular algorithm which is presented below is also suitable to analyze systems which include non-linear (viscous) damping elements.

METHOD

The modal time-history method is one of the methods generally accepted for dynamic analysis of power plant components. When using this method, the response is obtained by combining the response of all individual modes at a particular time. Those modes which are not in the analyzed frequency range can be accounted for by the rigid modes, so that the complete solution to a dynamic problem can be approximated using a limited number of modes. (For mathematical proof see e.g. Révész and Eitschberger, 1985)

Significant reduction of the computed stresses (compared to the response spectrum type of analysis) can be achieved using the modal time history method. The reduction is achievable in both cases; when support motion is the input for multi-level earthquake analysis, and also to analyze events described with time history input other than support motion, such as pressure, force or acceleration. The largest reduction in computed stresses have been reported repeatedly in cases (see e.g. Chiba et al., 1987) where the support could be considered with independent time-history input rather than using an envelop response spectrum for the entire system. This is obvious, for two excessive conservatism can be eliminated here. One of these conservatism was introduced with enveloping for all supports. Another was introduced when enveloping over the time (combining the maximum response of all modes gives must give higher results than the accurately calculated response at any time step, for it is highly unlikely that maxima of all modes occur at the same time.)

It is a standard approach to use the orthogonal damping method, i.e. frequency dependent structural damping. This implicates constant damping for a natural vibratory mode shape. The method used here reflects the fact that viscous damping elements, when introduced at several locations, will not change damping characteristics of natural vibratory mode-shapes, unless they are located where a particular eigenmode has a significant displacement component. Thus, the linear modal time-history analysis will be only modified inasmuch the time history input will be corrected at the location of the viscous dampers.

Performing time-history analysis of the piping system using the natural frequency mode shapes and the so called rigid modes has a number of advantages over direct integration. Perhaps the most important aspect is the transparency provided by the frequency analysis, and the use of expertise accumulated all over the world with the extensive use of the response spectrum method. It is important to keep in mind that, though direct integration is equivalent to a mode superposition analysis in which all the eigenvalues and eigenvectors have been calculated, the integration can only be accurate (and can only deliver conservative results) for those modes for which the time step is smaller than a certain fraction of the period. Thus effects of higher modes will eventually be filtered out by the direct integration method, whereas the modal time history analysis approximates these (often quite significant) load components with the rigid (left-out) modes. The conservativeness of the rigid mode approximation can easily be proved, both theoretically (Révész and Dalla Zuanna, 1985) and experimentally (Révész et al., 1984).

In cases when the displacement time-histories at the piping restraints are independent from each other support motion has to be transformed into load time histories at the individual nodes according to the equation

$$\mathbf{f}_p(t) = -\mathbf{M}\ \mathbf{K}^{-1}\ \mathbf{K}_B\ \ddot{\mathbf{x}}(t) \qquad \text{Eq. 1}$$

for the primary stress evaluation and

$$\mathbf{f}_s(t) = -\mathbf{K}_B\ \mathbf{x}(t) \qquad \text{Eq. 2}$$

for the secondary stresses, where $\mathbf{f}_p$ is the applied force vector for primary stress evaluation, $\mathbf{f}_s$ the load for secondary stress evaluation, **K** the stiffness matrix of the piping system, $\mathbf{K}_B$ the boundary coupling stiffness matrix, **M** the mass matrix and $\mathbf{x}(t)$ the time dependent displacement vector.

The analysis itself is time consuming. However, it does not require new developments, it is a straightforward extension of earlier introduced and tested analytical techniques and the additional efforts are moderate in cases when the time history type of analysis is required for other reasons. The modeling work to be done here depends mainly on the size of the problem, i.e. it is defined by the size of the systems and it is not influenced by the damping mechanism at the support.

The application of the method for piping with viscous dampers is based on the assumption that the punctual damping does not change drastically the behavior of the system, i.e. it is possible to repeat the same analysis of the computational model with or without viscous damping elements. The difference is that when using the Viscodampers, the solution will be received using the iterative formula

$$\mathbf{M}\ddot{\mathbf{x}}^{(n+1)} + \mathbf{K}\mathbf{x} = \mathbf{f} + \mathbf{f}_c(\dot{\mathbf{x}}^{(n)}) \qquad \text{Eq. 3}$$

where **f** stands for the applied force vector, and $\mathbf{f}_c(\dot{\mathbf{x}}^{(n)})$ for the vector of the correction terms. The time (velocity) dependent viscous damping effects in the force correction term are, as indicated, dependent on the actual velocity of the piping at the node where the support element is attached. Thus the viscous effects of the support are accounted for as a correction to the load and piping behaviour can be described with a linear model. Note, that complication necessary to get an approximated description of the system with the viscous damping element consists merely of the repeating of the time history analysis having modified the load description. Such a correction is a relatively easy task and has been implemented earlier (see Révész, 1983).

The modal time history method offers correct and conservative estimates which are substantially lower than what can be obtained by the response spectrum type of analysis. Therefore there have been numerous efforts to take advantage of this new approach even when time histories are not available, by generating time histories which would lead to identical frequency-acceleration response spectra. Indeed it is not too difficult to produce acceptable but lower results by scaling representative time histories.

In a recent paper Gruner and Jonczyk, 1988 compare results with 20 artificial time histories belonging to the same spectrum, and reports computed stresses scattered ± 13 percent whereas the piping support loads scatter ± 23 percent. On the other hand reductions of a magnitude have occasionally been produced. Therefore, even if an uncertainty margin of 26 percent (respectively 46 percent) is to be added to the results obtained for a transient, these are to be added to the values reduced before, possibly by a magnitude, and there will remain a significant gain.

RESULTS

Some simple principles have been presented above. The numerical implementation of these in case of a software for analysis of large nuclear piping systems, however, may be involved. With a comparison it will be demonstrated here, that there is a fair chance that the additional numerical work will be rewarded.

To investigate dynamic response of piping with different support conditions a typical large-bore piping system was designed and constructed to Class 2 specifications (Keowen et al., 1985). This was a pressurized sixty-foot section of an 8-inch and 6-inch Class 2 piping with multiple elbows and a simulated motor operated valve on a system of shaking tables. Recorded time histories from this experimental analysis have been used for the presentation here. For the response-spectrum time of analysis the recorded time histories have been used to compute the four response spectrum, then the envelope. The response spectrum method was applied in the frequency range up to 33 Hz, whereas the multi-level time-history method in the frequency range up to 100 Hz. Rigid mode approximation for the left-out modes are taken into account in both cases.

Figure 1 shows the distribution of the internal moment components, in global coordinates, as they result from the response spectrum method. Figures 2 and 3 then present the stresses in the individual finite elements of the piping model, indicating the computed stresses as compared to the allowable stress limit, with and without the stress intensification factors (as prescribed by the ASME BPV Codes for bends, tees, reducers, etc.) The full lines in these plots represent stress ratio distrubutions over the piping element as computed from the resultant moment, and the dashed lines show those computed stresses ratios which cover the stress intensification due to discontinuities. The two results have been obtained for the same loading with different methods. The one magnitude difference between the response spectrum and the multiple support time history method is reproduced in these calculations. The experimental values agree well with those results produced by the modal time history analysis.

Another example is a system which is punctually dampened with viscodampers. The effect of the viscodamper can be accurately described by Eq. 3 from above when using the linear modal time history analysis with independent support motion as input. As reported by Révész and Schwahn, 1988 the computational results are in conformity with the extensive experimental verification material from the work performed earlier by Keowen at al.

The algorithms outlined above have been programmed (Révész and Gordis, 1987) and are available on a series of computer hardware to anyone who needs them.

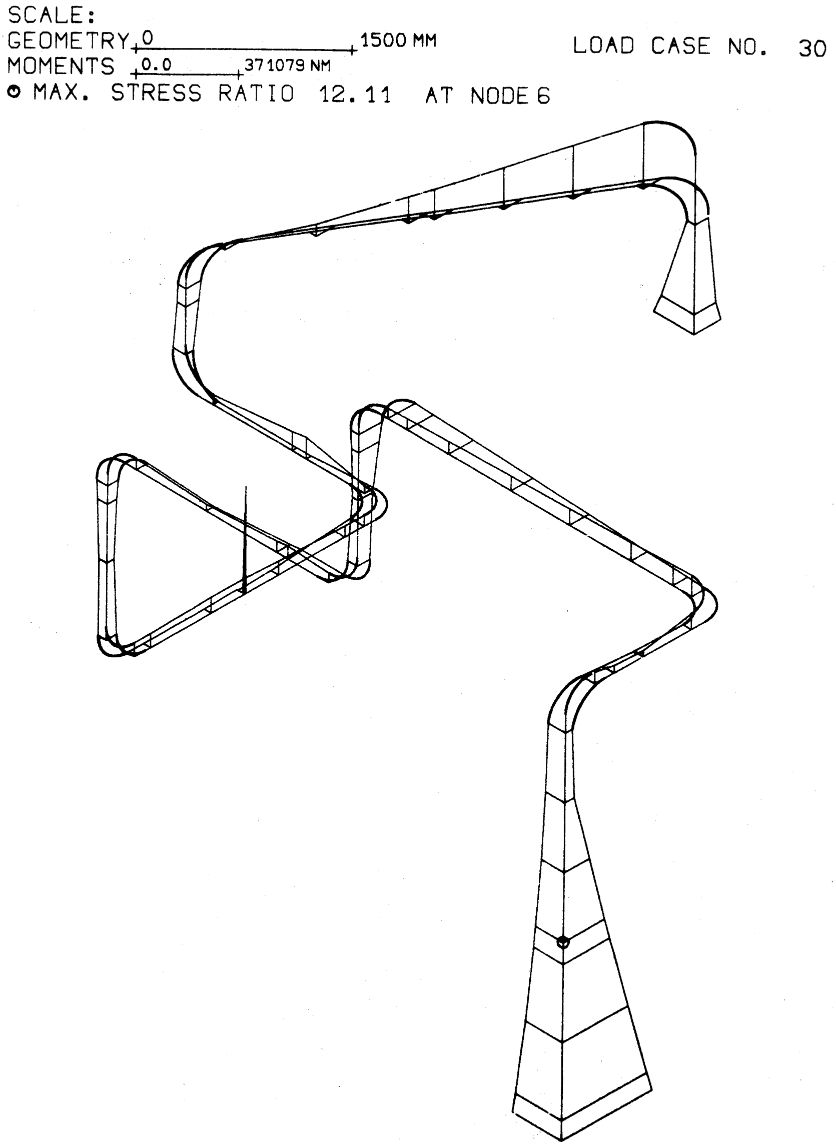

Figure 1: Distribution of the internal moments with response spectrum analysis

CONCLUSION

Finite element programs can be prepared with modest change to get better estimates for piping system behavior in cases when time history type of input is available or can be generated. With the natural frequencies and the pertaining mode shapes solution to the multiple support excitation problem can easily be constructed. With iterative approximation such a model is also suitable to describe non-linear piping elements (such as viscodampers) describing the nonlinear effect on the right hand side of the equation of movement (i.e. as a correction to the load). The time history modal method offers advantages of both, the direct integration and response spectrum method; transparency, stability, accuracy and reliability. Though the method is computationally intensive, the software is easy to use, and allows substantial reduction of computed stresses for dynamic analysis of a series of postulated events and also to quantify the very desirable effects of viscodampers.

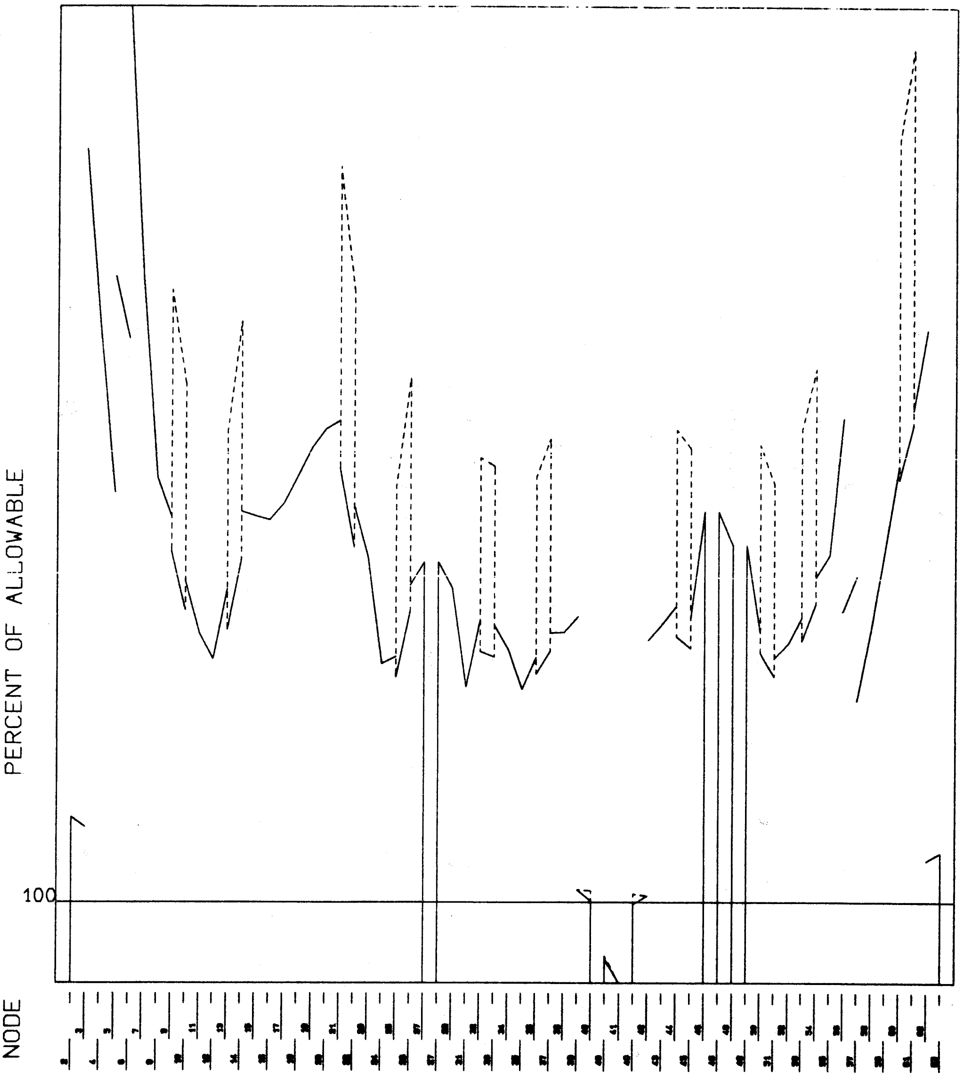

Figure 2: Distribution of the element stresses with response spectrum method

REFERENCES

ASME BPV Codes (an American National Standard), Section III, Rules for Construction of Nuclear Power Plant Components, Division 1 - Appendix N, Dynamic Analysis Methods, ASME, New York, 1986

Chiba T., Koyanagi R., Ogawa N., and Minowa C., 1987, "An experimental study of the response of the multiple support piping systems," Proc. 9th Int. Conference on Structural Mechanics in Reactor Technology (SMIRT), Rotterdam, Balkema, Vol. K2, pp. 975-980

Gruner P., J. Jonczyk: Sensitivity of the response of piping systems due to variation of important parameters, in Seismic Engineering - 1988, ed. by Liu T.H., L.H. Geraets at al., New York, ASME PVP - Vol. 144, 1988, pp. 25-30

Keowen R.S., Ibanez P., Johnson B. A., and Merz K. L., "The Comparative Dynamic Response of Typical Class 2 Piping with Different Support Conditions," Culver City, ANCO Engineers, Inc., 1985, p. 20

Révész Zs.: Analysis of Hydrodynamic Transients in Thin-walled Piping Applying Mass-correcting Forces, Trans. 7th Int. Conf. Structural Mechanics in Reactor Technology, Amsterdam, Elsevier, 1983, Vol. B, pp. 219-228

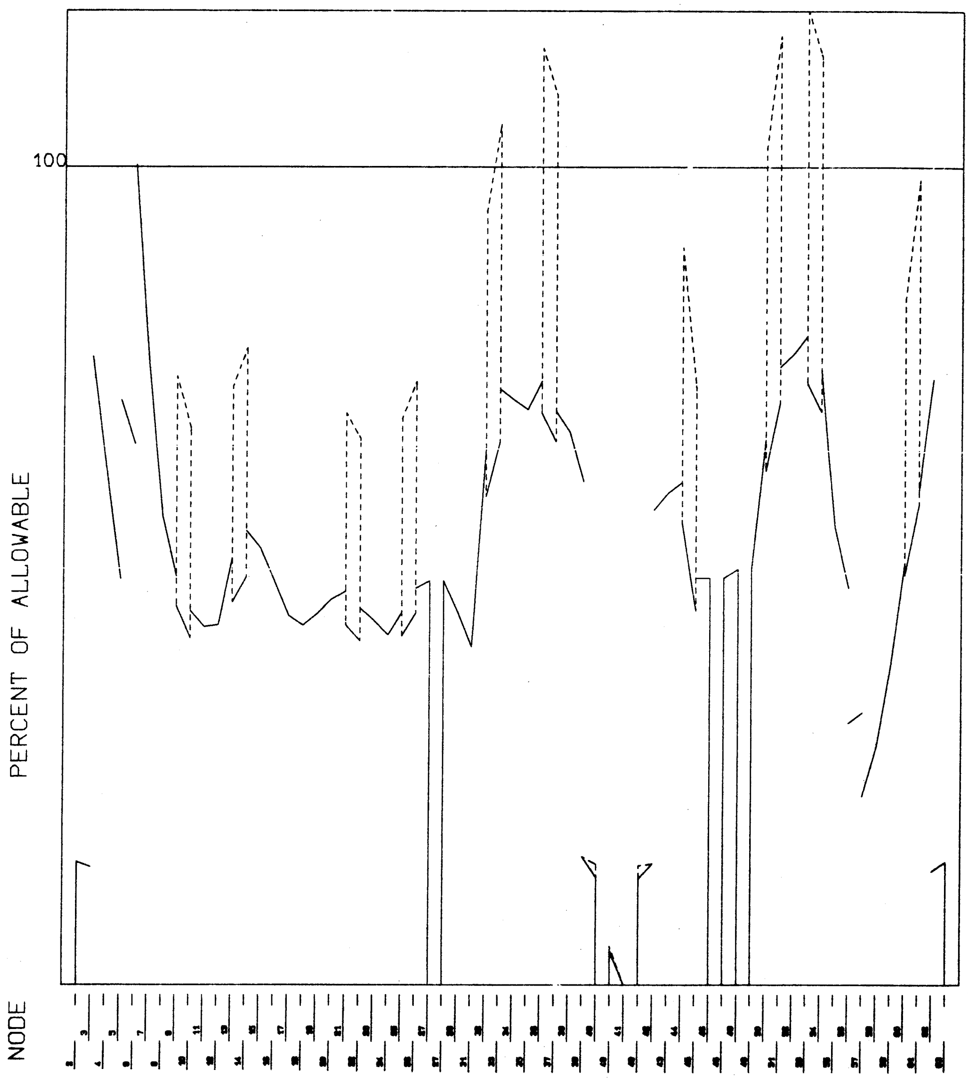

Figure 3: Distribution of the element stresses with modal time history analysis using displacement input at supports

Révész Zs., Dalla Zuanna M., "Vibration Analysis of piping mounted in a deep narrow shaft," Soil Dynamics and Earthquake Engineering, ed. C.A. Brebbia et al., Berlin, Springer Verlag, 1985, pp. 4-71 to 4-80

Révész Z., H. Eitschberger: Vibration Analysis of a Non-Accessible Piping Section under Unknown Loading, Trans. 8th Int. Conf. Structural Mechanics in Reactor Technology, Amsterdam, Elsevier Science Publishers, 1985, Vol. DFG, pp. 627-633

Révész Zs., F. Ferroni, L. Bollok: Verifying Computations for Advanced Piping Problems with in situ Measurements, Computational Methods and Experimental Measurements, ed. G.A. Keramidas and C.A. Brebbia, Berlin, Springer Verlag, 1984, pp. 8-37 to 8-48

Révész Zs., Gordis K.: PSTAR - Piping Stress Analysis and Reporting, Structural Analysis Systems, Vol. 6, ed. A. Niku-Lari, Oxford, Pergamon Press, 1987, pp. 115-130

Révész Zs., K.-J. Schwahn: Analysis of Piping Systems incorporating Viscodampers, in Seismic Engineering - 1988, ed. by Liu T.H., L.H. Geraets at al., New York, ASME PVP - Vol. 144, 1988, pp. 81-86