Response of HDR–VKL Piping System to Seismic Test Excitations – Comparison of Analytical Predictions and Test Measurements

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INTRODUCTION

As part of the earthquake investigations at the HDR (Heissdampfreaktor) Test Facility in Kahl/Main, FRG, simulated seismic tests (SHAM) were performed during April–May 1988 on the VKL (Versuchskreislauf) piping system. The purpose of the SHAM tests was to study the behavior of piping subjected to a range of seismic excitation levels including those that exceed design levels many times and might induce failure of pipe supports or plasticity in the pipe runs, and to establish seismic margins for piping and pipe supports. Data obtained in the tests are also used to validate analysis methods. Detailed reports on the SHAM experiments are given elsewhere (Kot et al, 1988).

The objective of the work reported here is to evaluate a subsystem analysis module of the SMACS code (Maslenikov et al, 1985). This module is a linear, finite-element-based program capable of calculating the response of nuclear power plant subsystems subjected to independent multiple-acceleration input excitation. The evaluation is based on a comparison of computational results of simulated SHAM tests with corresponding test measurements.

DESCRIPTION OF TESTS

Figure 1 shows a view of the piping system, the VKL. The pipe runs of the VKL, excluding the HDU vessel, cover about 10 m in the vertical direction, about 11.5 m in the x direction, and about 6 m in the z direction. The pipes are of stainless steel, ranging from 100 to 300 mm in diameter. The HDU vessel was fixed at its base, and displacement restraint in the x and z directions was provided by a structural frame at about a third of the height from the top of the vessel. The DF15 manifold was directly attached to the floor as indicated in Fig. 1. Different seismic support configurations were used during the dynamic tests. Figure 1 shows a configuration typical of U.S. nuclear power plants, with struts and snubbers. It is designated the NRC configuration for identification only. The other support configuration covered in this paper is designated the KWU configuration. The differences between the NRC and KWU configurations are that the latter had no snubbers, had one less strut (H3 having been removed), and had larger struts at H9, H10, and H11.

During the SHAM tests, the dynamic excitation was applied along the x direction to two different points of the piping with the H5 and H25 actuators as shown in Fig. 1. The excitation time histories represent an integral multiple of a hypothetical safe-shutdown earthquake (SSE) with a zero-period acceleration of 0.6 g. Although the intent was to apply the same excitation at the two points, the recorded accelerations on the two actuators were somewhat different, as may be seen from Fig. 2. The solid line of Fig. 2 represents the target response spectrum of the hypothetical SSE, and the dashed and dotted lines represent the actual response spectra at the actuators. The tests covered a range of excitation levels, with the higher levels inducing plastic strains in the pipe. However, the present paper concerns the lowest levels of excitation (100% SSE) of the NRC and KWU configurations so as to justify the assumption of elastic material behavior in the analytical simulations.

About 300 channels of response were recorded during each test. The response quantities measured in the tests were pipe strains; accelerations on the pipe and the actuators; displacements on the pipes, actuators, and pipe supports; and forces in the supports and actuators. After the application of a two-stage low-pass filtering that eliminated frequency contents greater than 60 Hz, the data became available in the form of time histories.

ANALYTICAL SIMULATIONS

Both pretest predictions and posttest simulations of the response of the VKL system were made with a module of the SMACS code. This module computes the response of subsystems subjected to independent multisupport excitations. The results of the time domain analysis were obtained as histories of various response quantities, i.e., accelerations, displacements, support forces, and pipe stresses.

Description of Method

The SMACS analysis of subsystem response to independent multisupport excitations is based on the pseudostatic-mode method (Johnson et al, 1981). The unknown nodal displacement is the sum of pseudostatic and dynamic portions. The pseudostatic portion is the response induced in the system due to support motions, excluding inertia effects. The dynamic portion is the response due to inertia effects only. A static analysis run of a finite element code, based on the SAP4 program, computes the pseudostatic modes, and a modal analysis run of the same code computes the eigenfunctions, assuming proportional damping. The response recovery runs compute the two portions of the response for specified modal damping and combine them to give the total response for prescribed independent support accelerations. Both the prescribed accelerations and the computed total responses (accelerations, displacements, and forces) are in the form of time histories. Damping values may be specified in a few different ways; these include the PVRC criteria, which specify the modal damping to be 5% or 2% of critical damping for modes of frequencies less than 10 Hz or greater than 20 Hz, respectively, and linearly interpolated for modes of frequencies between these points.

Finite-Element Model

The entire system shown in Fig. 1 was modeled with pipe and truss elements only. The HDU vessel, the DF15 and DF16 manifolds, the spherical tee, and the valves were all approximated with pipe elements. The connections of the HDU vessel to the nozzles at its top were represented by artificial pipe elements of equivalent stiffness and zero mass density. Concentrated masses were added to the appropriate nodes to represent the actual masses of the parts being modeled. A similar technique was used for modeling the tees and the valves. The model comprised 126 straight pipe elements and 28 curved pipe elements. The total mass of the model, including the concentrated masses, was 78,400 kg.

The pipe supports were modeled with truss elements. The constant-force hangers (H16, H17, H18, and H19) were ignored since they were assumed not to respond to dynamic excitation. Although appropriate stiffnesses were assumed to represent each remaining pipe support, no distinction was made as to the behavior of struts, snubbers, or spring hangers when subjected to dynamic excitation.

The truss elements were assumed to be hinged at their wall end and attached directly to the pipe nodes at the other end. Displacement and rotation restraints were specified at the appropriate nodes of the elements representing the HDU vessel and the DF15 manifold. The prescribed accelerations were applied directly to the pipe at the two nodes corresponding to the actuator attachment points.

Pretest Predictions

The primary purpose of the pretest predictions was to estimate stresses in the system for test planning. These predictions were limited to the NRC configuration. Many prediction computations were made for different hypothetical modifications of this configuration. Comparisons of the pretest predictions with the test response have been reported previously (Kot et al, 1988). The comparisons showed that the peak values of support forces were generally underpredicted, often by factors of two or more. However, the predicted strains in the pipe were closer to the measured strains though they were smaller than the measurements. No ready explanation could be found for the differences between the predictions and measurement. However, the test data showed significant differences between the excitations at H5 and H25, as may be seen from Fig. 2. It was expected that more realistic results would be obtained if the recorded actuator accelerations were used as input in the computations. The remainder of the paper focuses on the posttest analyses based on such an approach.

Posttest Analysis

The posttest calculations are not blind predictions in the strict sense because part of the test measurement (the recorded accelerations at H5 and H25) is used as input. However the finite-element model remained essentially unchanged from the pretest computations for the NRC configuration. Minor changes were made to reflect the actual boundary conditions of the DF15 manifold, and the stiffnesses of the spring hangers were revised as additional information became available. In addition, calculations were made for the KWU configuration. The finite-element model for the KWU configuration was obtained by deleting the elements representing the snubbers and the strut that were dropped from the NRC configuration.

Table 1 gives the first ten modal frequencies obtained from the eigenfunction analysis for the two configurations. Actually, 25 modes were included for the response calculations. The natural frequency of the 25th mode was 32 Hz for the NRC configuration and 26.5 Hz for the KWU configuration.

Table 1. Calculated Modal Frequencies

Mode No.	1	2	3	4	5	6	7	8	9	10
NRC Configuration	5.61	5.64	8.05	8.21	8.79	9.49	10.75	10.91	15.04	15.79
KWU Configuration	2.15	2.68	3.31	5.49	5.59	5.80	7.07	7.59	8.18	9.32

Like the pretest calculations, the first set of posttest calculations was based on the PVRC criteria for damping. For the second set of calculations, a uniform modal damping of 3% of critical damping was assumed. Results of simulations of the 100% SSE excitation for the two different damping criteria are reported here. Ideally, a single time history would represent the excitation at both H5 and H25; however, as noted before, the acceleration recorded on the piston of each actuator was different in each test. Figure 2 shows this for the 100% SSE test of the NRC configuration. The target spectrum corresponding to the idealized time history is also shown in this figure.

The calculated response quantities included accelerations, displacements, and forces. Time domain plots of the latter two quantities revealed that baseline correction was required before they could be compared with the corresponding test records. The baseline correction involves the removal of both a polynomial trend and some long-period oscillations. Because these corrections have not yet been completed, this paper presents only the acceleration response results.

Comparisons

Thirty-two channels of response acceleration were computed for each test. These corresponded to 32 channels of measurement at 11 locations distributed over the entire piping system. To facilitate comparisons, response spectra for 4% damping were derived from both the computed and measured sets of accelerations. Figure 3 shows accelerations for the NRC configuration at a point identified as RS761 in Fig. 1. Since the agreement between test and analysis varied from channel to channel, no typical location would characterize the general quality of the computed results. The figures indicate that for some channels the agreement was good and for others it was not. Qualitatively similar comparisons were observed for the KWU configuration.

As Fig. 3 shows, the most prominent responses along the horizontal (x and z) axes are better matched by the computations than the response along the vertical (y) axis. For almost all locations, the computed response along the vertical axis was significantly lower than the test measurements. Changing the damping criteria from PVRC to a uniform value of 3% brought the computed responses closer to the test records in general; however, most vertical axis responses remained much lower than their test counterparts. Even along the x direction, the agreement between calculations and measurement is better at lower frequencies, i.e., up to about 7 Hz. Figure 2 shows that the excitation begins to decrease for frequencies above 7 Hz, though it increases again at higher frequencies. Since the cut-off frequencies specified in the analysis might have been too small compared to the frequency content of the excitation, the missing contribution from higher modes could be responsible for the greater discrepancies at higher frequencies.

In a somewhat similar effort, other investigators (Bezler et al., 1985) noted that the deviation of calculated results was greatest near supports. Such an observation could not be made in the present case because no location for which acceleration was calculated was very near any support, and no pattern was apparent in the magnitude of deviations.

Preliminary comparisons based on displacements and forces suggest that in general these responses are significantly underpredicted. However, this observation remains to be confirmed.

CONCLUSIONS

On the basis of the comparisons of accelerations alone, the code computations tend to give mixed results. Some of the horizontal components (along x and z direction) of accelerations are close to the test measurements, especially if the damping assumed is lower than the PVRC criteria. However, this agreement is not uniform. The vertical component (y direction) of accelerations is generally very much underpredicted. The question of whether the underpredictions result from deficiencies in the model or from assumptions in the methodology of the computational code remains to be addressed. One would have to employ the same model in other computational codes on the one hand, and recompute the results after including more of the higher modes on the other hand, to resolve this question.

ACKNOWLEDGMENT

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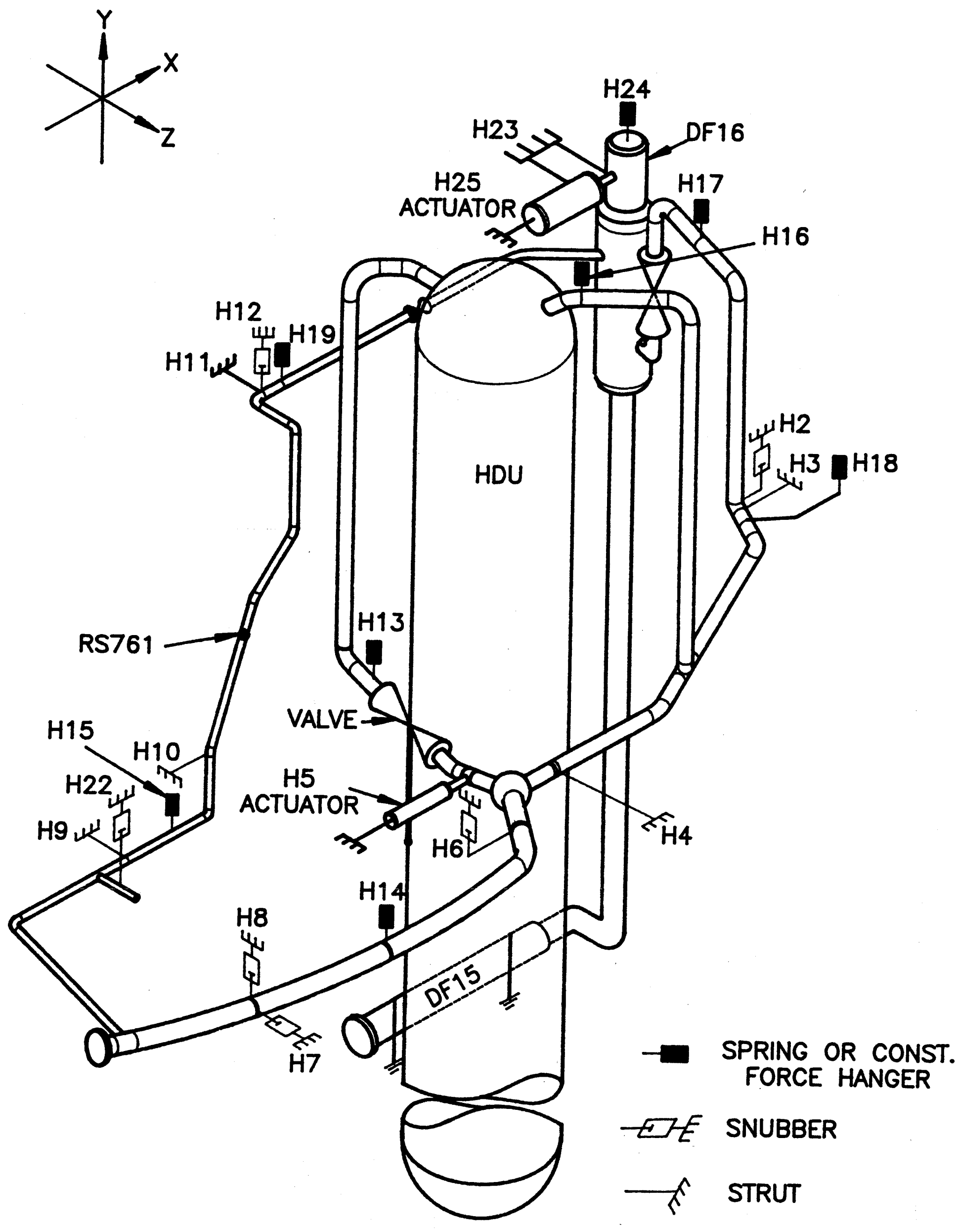

Figure 1. VKL Piping System: NRC Configuration for SHAM Tests

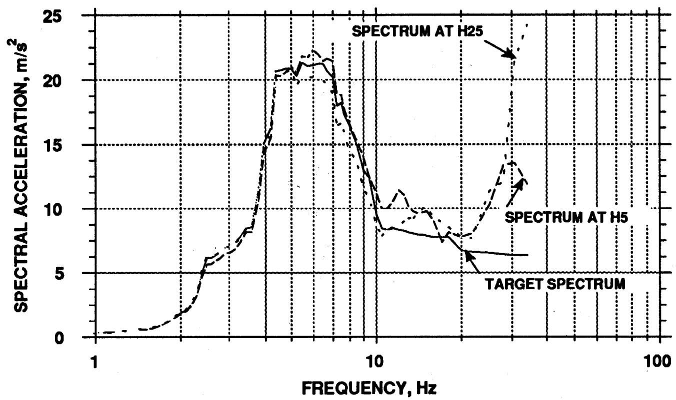

Figure 2. Response Spectra for 4% Damping: NRC Configuration, 100% SSE Excitation

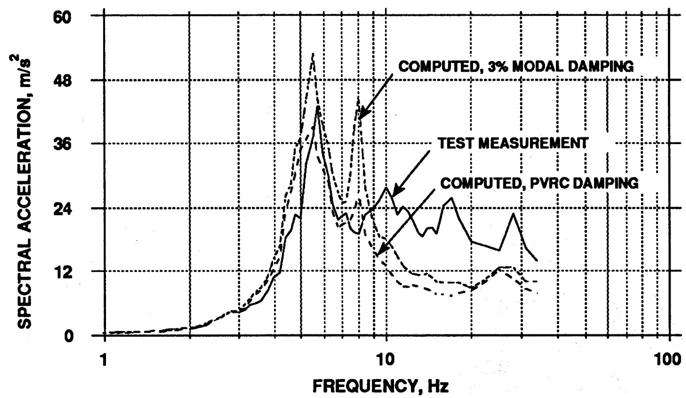

Figure 3(a). Response Spectra for 4% Damping: NRC Configuration, Response at RS761, along x Axis

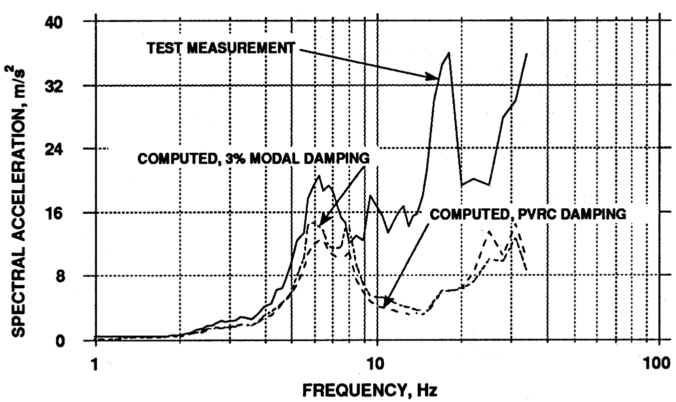

Figure 3(b). Response Spectra for 4% Damping: NRC Configuration, Response at RS761, along y Axis

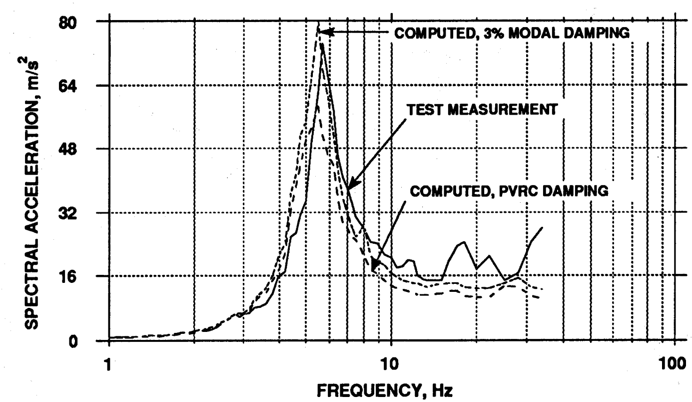

Figure 3(c). Response Spectra for 4% Damping: NRC Configuration, Response at RS761, along z Axis