Piping Response to Blowdown: Pretest Prediction vs. Experimental Results

W.B. Walton, G.E. Howard, B.A. Johnson, S. Griffith
ANCO Engineers, Inc., 9937 Jefferson Blvd., Culver City, California 90230, U.S.A.

Summary

A structural dynamic simulation was conducted to predict the structural response of a nuclear power piping system to severe thermal-hydraulic loads. The simulations were part of the series of "blind" calculations sponsored as part of the Heissdampfreaktor Safety Research Program, Federal Republic of Germany. The results of one such simulation and comparison to experimental behavior is reported herein.

1. Introduction

A series of simulations* and severe thermal-hydraulic transient experiments† involving an 0.4 m diameter nuclear power piping system were conducted to test simulation procedures. Discussed herein is German Standard Problem 4a (DSP4a) which focused on the piping structural dynamic response to transient flows arising from simulated pipe break conditions. Figure 1 shows the test assembly. Flow conditions prior to blowdown were: pressure, 70 bar (1015 psi); temperature, 220°C (428°F); flowrate, 4 m/sec (13.1 ft/sec).

2. Description of German Standard Problem 4a (DSP4a)

DSP4 involved experimental simulation of an assumed break in a feedwater line for a nuclear power plant. The simulation was performed using a leg (portion) of the modified recirculating loop of the Heissdampfreaktor (HDR) at Kahl, West Germany (see Figure 1). The test involved circulating compressed water through a portion of the pipe system. The circulation started from the S-support 3 (see Figure 1) and travelled to a spherical piece 12, and on through locations 6, 7, 5, 11, 10, 4, 9, and back to the reactor vessel 2. Once steady-state fluid conditions were achieved, the break in the feedwater line was simulated. At check-valve closure, high amplitude pressure waves were generated which propogated through the system. For this reason it was of importance to understand the structural dynamic behavior of the pipe system during the fluid dynamic event. This is where DSP4a ties in with DSP4. For DSP4a, the structural dynamic behavior of the URL test pipeline was to be theoretically determined; applied structural loading was to be determined from the DSP4 test data.[1] During the blowdown test the URL pipe was instrumented with displacement transducers, accelerometers, and strain gauges. The data from these instruments provide the basis for comparison with the DSP4a simulation results.

The portion of the URL system involved in the structural simulation extends from location 2 through locations 13, 9, 4, 10, 11, to location 8. The pipe begins at the reactor vessel and travels to a rupture disk at its other end. There is a fixed point near the rupture disk. There are no structural supports (snubbers or struts) attached to the pipe. The inner pipe diameter and wall thickness vary from 0.351 to 0.453 meter and 0.014 to 0.142 meter, respectively.

The fluid forces on the pipe, due to the pressure waves, were to be calculated using the DSP4 test data (i.e., fluid pressure). The pressure as a function of time was known at numerous locations, particularly at inlets and/or outlets of pipe elbows. The method used for obtaining the forces was to be developed by each investigator. Thus, DSP4a involves determining both the fluid/structure interface forces and the structural response.

3. Structural Model of the URL Pipe System

To simulate the dynamic behavior of the URL pipe structure for DSP4a, a linear finite element model was constructed. A plot representing the model is shown in Figure 2. Fixed points (all degrees of freedom constrained) were assumed at each end of the pipe. The

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model was defined using 30 nodes and 27 finite elements (straight and curved pipe elements). The ASME Boiler and Pressure Vessel Code defined flexibility factor k_p was used to modify the bending terms in the flexibility matrix for the curved pipe element. This correction can be significant. From experience, errors on the order of 25% have been observed in the first natural frequency of piping systems when this correction was not included. Following model formulation, an eigenvalue analysis of the URL model was executed. The first five (5) eigenfrequencies are given in Table I. The experimentally determined eigenfrequencies are also presented. There is excellent agreement between the results.

4. Pressure Wave Forces on the URL Pipe

DSP4a involves accurately simulating the structural dynamic response of the modified URL system when excited by the DSP4 blowdown fluid forces. This type of simulation deals with fluid-structure interaction. There are two general approaches to the fluid-structure problem--coupled and uncoupled solutions; the latter approach was used herein. This involved using the experimental fluid response data, obtained from the DSP4 problem, to calculate the fluid-on-pipe forces due to the blowdown event. There are several approaches that can be used to determine the fluid forces. The one selected involved the use of the linear momentum equation from fluid mechanics (control volume formulation).[2]

To apply this equation, the space occupied by the fluid in the pipe was subdivided into control volumes (the union of the control volumes is equal to the total space in the pipe). There are an infinite number of ways to subdivide the space. Constraints on the selection of control volumes were: (1) the pressure had to be known at each end of a volume; (2) a finer distribution of volumes would more closely simulate the load distribution (each volume with one resultant force). On the basis of the above discussion, the URL blowdown model (DSP4a) was broken up into six (6) control volumes. Four of the volumes were made up of a combination of straight and curved sections. Two of the volumes were straight.

In calculating the fluid forces on the pipe, it was assumed that the contribution of the momentum terms was negligible--the fluid forces were due largely to the pressure waves and not to the net flow of fluid. Using this assumption, the momentum equation (control volume formulation) reduces to $\bar{F}_S = 0$ (the sum of the external surface forces equals zero). This equation is applied to an arbitrarily shaped control volume (for a piping system) as shown in Figure 3. The only forces of concern are the pressure forces (forces on the control volume from the adjacent fluid) and the force of the pipe on the volume. It is seen that the resultant force of a control volume (using the above assumptions) on its corresponding section of pipe is given by

$$\bar{F}_R = p_1 A_1 \hat{i}_1 - p_2 A_2 \hat{i}_2$$

This equation was applied to each of the control volumes used to define the URL space.

5. Structural Dynamic Simulation of URL Blowdown Event (DSP4a)

The finite element model discussed in Section 3. and the fluid forces presented in Section 4. were the basis for the response calculations required for German Standard Problem 4a (DSP4a). In performing the response calculations, several items were of concern; they were: (1) damping to be used; (2) the integration interval; and (3) nonlinear versus linear simulation approaches. Proportional damping was used to model any damping effects. The proportional damping coefficients α and β ($C = \alpha M + \beta K$, where C, M, and K are the damping, mass, and stiffness matrices, respectively) were chosen to be 1.20 and 6.35×10^{-5}, respectively. This gave an equivalent modal damping of 2.0% at 5 Hz and 100 Hz and a minimum damping of 1.0%. It was believed that this was consistent with previously obtained damping data for another portion of the URL system. Also, it was expected that the solution would not be too sensitive to variations in the damping.

The structural equations of motion were integrated using a direct integration scheme (Newmark method). The integration interval was chosen to be equal to the discretization interval used for digitizing the DSP4 data ($\Delta t = 0.0002$ second). With this time interval and using 16 time points per cycle, it is possible to define a transient signal of up to 312.5 Hz. The fluid pressure, for DSP4 type events, generally has its major frequency content in the 50 Hz to 100 Hz range. Hence, the chosen integration interval should be more than adequate.

In simulating the structural dynamic event, a linear analysis approach was selected because nonlinear pipe material behavior was not expected.

Comparisons are made between the simulation and experimental results in Figures 4 through 6. The predictions overestimate the actual results. The agreement is moderately good for some of the results and poor for others. The prediction shown in Figure 6 shows a large high-frequency component in the signal; if it was filtered out, the comparison would probably be good. Some of the error is attributed to the limited number of control volumes that could be used. Table II gives a comparison of the peak displacements.

6. Comments

The simulation performed produced conservative results, which could be improved on by increasing the number of control volumes. It appears that the assumption that the fluid-on-pipe forces were due mainly to the pressure waves was reasonably valid.

References

[1] Walton, W.B., Howard, G.E., Johnson, B., "German Standard Problem 4a," NUREG/CR-2390.

[2] Shames, I.H., "Mechanics of Fluids," McGraw-Hill Book Company, 1962.

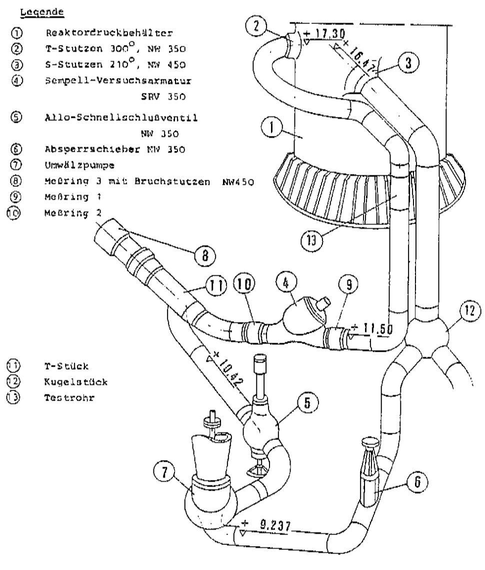
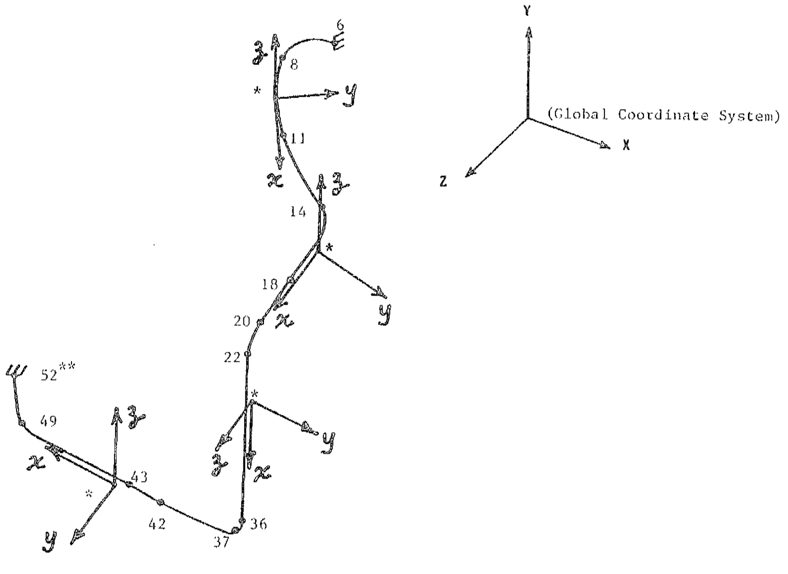


Figure 1: Modified Primary Coolant Loop at HDR



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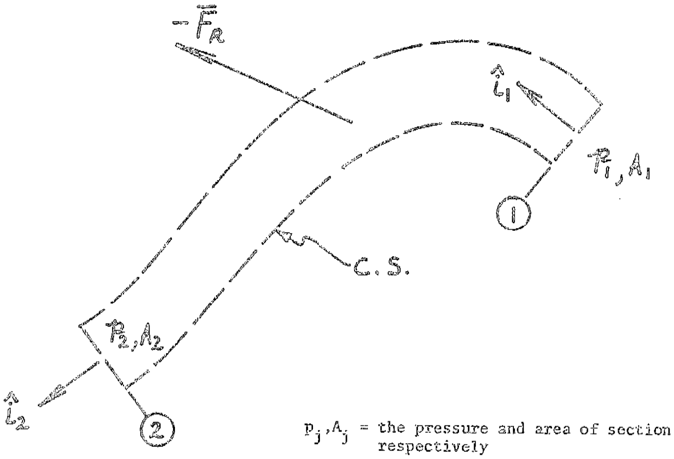
*These local coordinate systems (x,y,z) are for output of displacements and accelerations.

**Only select node numbers are shown.

Figure 2: ANCO Structural Model



p_j, A_j = the pressure and area of section j, respectively
$\hat{i}_j$ = the tangent unit vector at section j
$\bar{F}_R$ = resultant force of the control volume on the pipe

Figure 3: Arbitrarily Shaped Control Volume for Obtaining Pipe Segment Forces.

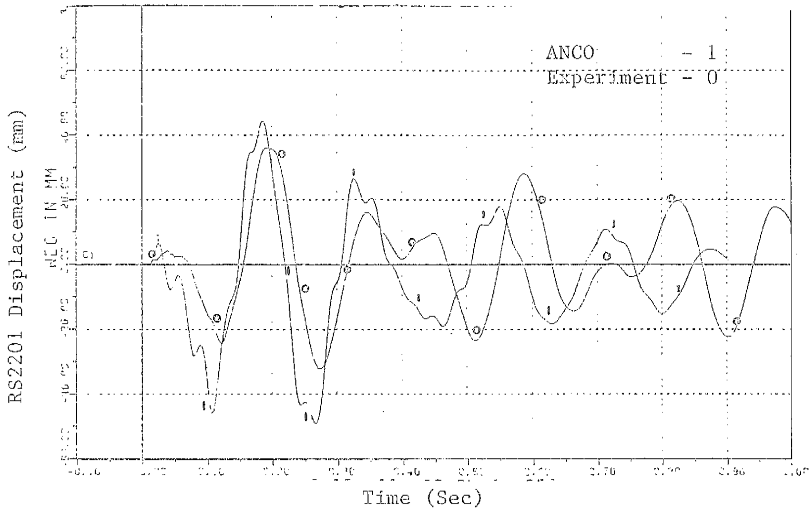


Figure 4

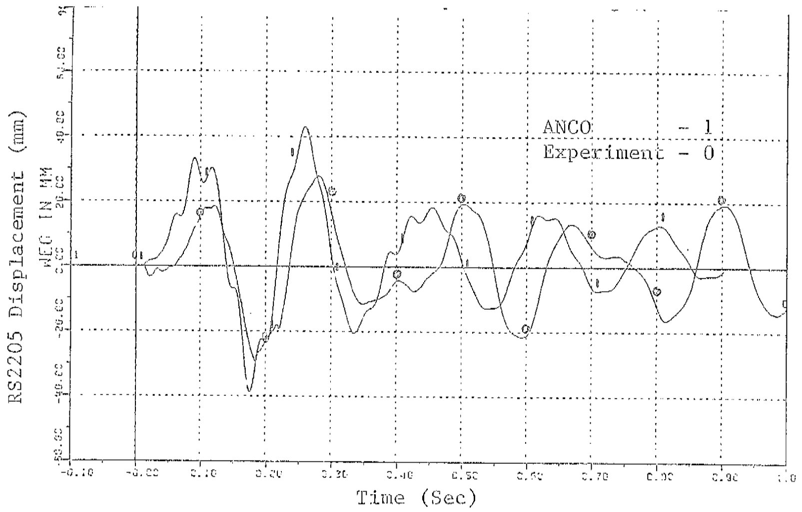


Figure 5

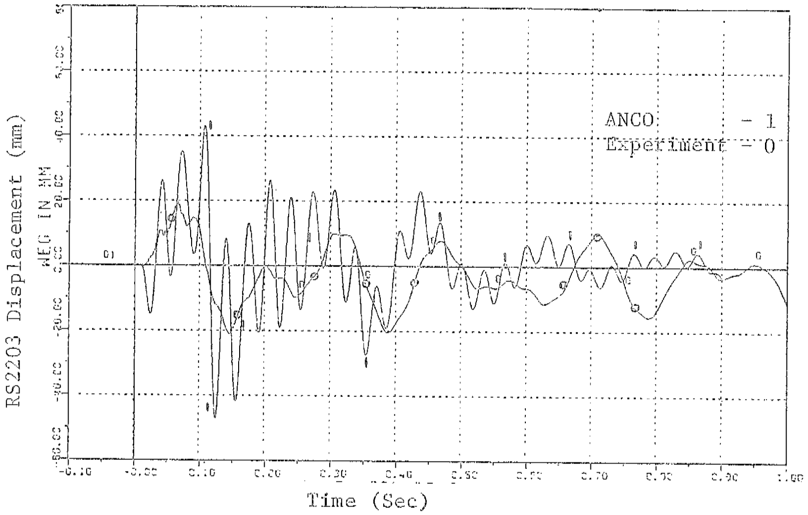


Figure 6

Table I
COMPARISON OF EXPERIMENTAL AND THEORETICAL EIGENFREQUENCIES

Mode	Experimental Eigenfrequency (Hz)	Predicted Eigenfrequency (Hz)	Relative Difference (%)
1	4.95	5.46	10.3
2	7.75	8.54	10.2
3	*	9.43	*
4	25.50	26.18	2.7
5	29.30	30.55	4.3

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*Note: On the assumption that the first two experimental eigenfrequencies correspond to the first two theoretical eigenfrequencies, either there is not an experimental mode that corresponds to the thrid theoretical mode (9.43 Hz eigenfrequency mode) or the third experimental mode was not observed during analysis of the experimental data by German investigators.

Table II
COMPARISON OF MAXIMUM AND MINIMUM DISPLACEMENTS

	Minimum/Maximum Value (mm)		
Transducer	Experimental	Predicted	Relative Difference (%)
RSS2202	-7/9	-20/20	186/122
RS2201	-35/37	-49/44	40/19
RS2203	-22/18	-47/43	114/139
RS2206	-/-	-50/41	-/-
RS2204	-52/62	-87/67	67/8
RS2205	(-30/30)*	-39/43	30/43
SS4005	-7/8	-1/2	85/75
SS4004	-23/27	-18/21	22/22
SS4006	-13/17	-15/18	15/6

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*Note: Displacement transducer may have been damaged during the test.