HDR Steel Containment Vessel Dynamic Inertance Tests

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Summary

Modal (inertance) tests were conducted on two vessels at the Heissdampfreaktor (HDR) facility located 25 kilometers east of Frankfurt, Federal Republic of Germany. The specific purpose of the tests was to determine the modal properties (frequencies, mode shapes and associated damping ratios) of the test vessels over a frequency range of 1 to at least 33 hertz (Hz) using either an impulse hammer or shaker as a source of input excitation. The results of these tests are intended for use by the U.S. Nuclear Regulatory Commission (NRC) in developing standards for modeling similar structures.

Excitation or input forces together with measured vessel responses were processed by a digital modal analyzer. Frequency response functions and associated data were determined and stored on magnetic disks while at HDR. These results were then further processed for determination of the modal properties.

A large number of relatively uniformly distributed modal frequencies with associated damping ratios from 2% to 4% of critical were found from evaluation of the frequency response functions.

The modal response of the vessel shows the structure to be quite complicated in its behavior. A number of mode shapes are complex which indicates nonproportional damping is present.

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1. Introduction

Inertance (vibration) tests of two vessels at the Federal Republic of Germany's Heissdampfreaktor (HDR) facility were conducted during May and June 1982 by EG&G Idaho, Inc. The task objective was to determine, in more depth than previously obtained, the modal properties (frequencies, mode shapes and associated damping values) of each vessel using two different test methods for comparative purposes. The work was sponsored by the U.S. Nuclear Regulatory Commission (NRC) in cooperation with Kernforschungszentrum Karlsruhe (KfK) of F.R. Germany. Results of the work are in support of NRC's development of standards for modeling similar vessels and KfK's Earthquake Investigations Project which is part of their larger HDR Safety Program.

One of the vessels tested was the steel containment vessel (SCV), as shown in Figure 1, which is approximately 60 meters high and 20 meters in diameter. This report presents the results of the test effort wherein an extensive instrument grid was employed on the vessel so that both beam and shell modes of vibrational behavior could be determined. Furthermore, the vessel was subjected to impact and random force shaker excitation such that subsequent analysis of the recorded data could be compared over a frequency range of 1 to at least 33 Hz for each type of excitation.

2. Test Vessel Description

The SCV is one of four major components comprising the HDR reactor building. The other three, all constructed of reinforced concrete, are the massive foundation mat, the internal support structure, and the outer containment shell as shown in Figure 1. The foundation mat provides principal support for the other three major components while the internal structure (located within the SCV) supports the reactor vessel, piping systems, and other related equipment. Significant items supported by the SCV are the attached personnel and equipment hatches plus the overhead crane located inside the shell near the junction of the cylinder and top dome.

The SCV is a free standing cylindrical vessel with hemispherical top and bottom heads measuring 20 meters in diameter. The lower 5 meters of the bottom head is encased by foundation concrete. The overall free standing height is 55 meters (5 meters-bottom head, 40 meters-cylindrical section, 10 meters-top head). The top of the inner structure is 35 meters above the foundation level (elevation 30 meters) and is termed the "operating floor." A 10 millimeter thick layer of plastic foam separates the inner concrete structure from the SCV.

A large penetration, termed "material hatch," is located at the operating floor level. In addition, several other randomly located penetrations are present around the circumference of the vessel.

Access to the outer surface of the vessel is provided by means of a ladder located at 55°, leading from the foundation to a catwalk (39.5 meters elevation) which encircles the vessel, a hand-powered personnel elevator which is suspended from the catwalk, and a curved ladder, pivoted at the top of the vessel and extending to the catwalk. The hand-powered personnel elevator was used to access the cylinder portion and the curved ladder was used to access the top head portion of the vessel.

3. Test Description

3.1 Instrument Grid and Geometry

Overall geometry, instrument location, and shaker location are illustrated in Figure 2.

A total of 62 acceleration measurement locations were present on the vessel. One quadrant of the vessel, from 210° through 300°, was instrumented at 30° circumferential intervals. Ten instrumentation elevation lines were located on the cylindrical portion of the vessel and two lines, at 30° meridional intervals, were located on the top head. An additional meridional instrument location line was located at 150° (ladder location). The shaker reference acceleration location, point no. 1, was located directly above the material hatch.

As schematically represented by Figures 3 and 4, all accelerometer coaxial cables for acceleration measurement at points 2 through 62 were coupled to the resident HDR data acquisition (cable protection) system through a termination box located near the foundation elevation at 150°. Acceleration measurement for point 1 was coupled to the resident HDR acquisition system through a termination box located at the operating floor.

3.2 Shaker Tests

A servohydraulic shaker system (power supply, controls, and shaker) was located on the operating floor. The shaker and reaction mass were oriented horizontally and attached to the material hatch penetration such that the resulting force was tangentially applied to the vessel through the material hatch. Acceleration of the reaction mass was monitored at the shaker control and coupled to the resident HDR data acquisition system through the operating floor termination box.

The servohydraulic actuator has a 13.3 kN static force rating. As schematically illustrated by Figure 3, the actuator is attached directly to the structure and the force input is accomplished by moving a reaction mass (~115 kg) attached to the actuator piston through a variable stroke length (up to ±50 millimeters) either randomly or sinusoidally. The shaker force input is directly proportional to the value of the output of the accelerometer mounted on the mass.

For all points on the vessel, frequency response functions (FRFs) were determined and stored for random excitation. Anti-aliasing filter frequencies were set at 50 Hz and low pass excitation signal filters were set at 100 Hz. In general, 120 acceleration history samples were measured for FRF averaging for each degree of freedom (DOF). Radial and tangential DOFs were defined at each point on the top head (points 2 through 14). Thus, a total of 135 DOFs were present on the vessel.

To provide increased energy input for low frequency response (1 through 10 Hz), additional sine sweep FRF determinations were made for DOFs at point 1. In this case, the excitation frequency was continuously swept from 1 through 10 Hz during which 120 samples were measured and averaged. Anti-aliasing filters were set, in this case, at 10 Hz.

3.3 Impact Tests

Impact testing consisted of measurement of the acceleration of a reference point on the vessel for instrumented impact at other points on the vessel.

The instrumented hammer used to excite the vessel was fitted with a 22.2 kN capacity load cell. A typical test setup using the hammer is shown schematically in Figure 4.

Three sets of radial impact tests were performed: (a) impact of points 13 through 62 with reference DOF measured at point 15X (radial), (b) and (c) two independent sets where the reference acceleration was DOF 17X and points along the 150° meridional instrument line were radially impacted (points 17, 22, 27, ..., 62).

For all impact testing performed on the SCV, anti-aliasing filters were set at 50 Hz and 20 impact acceleration and force histories were measured for each FRF determination. The instrumented hammer force and accelerometer response were coupled to the HDR data acquisition system through the termination box located at the foundation level in the annulus.

4. Results

4.1 Frequency Response Functions

During data acquistion, both FRFs and coherence Functions were obtained. Examination of coherence functions indicates relatively high (greater than 0.8) values in the vicinity of FRF resonances for frequencies greater than approximately 8 Hz for the majority of FRFs obtained. However, for both random shaker and impact excitation, coherence drops significantly for frequencies less than approximately 8 Hz. For the case of sine sweep shaker excitation, this roll-off coherence frequency is reduced to approximately 5 Hz. However, it should be emphasized that relatively low coherence does not render a FRF invalid. Rather, a significant noise signal is present which renders interpretation of the FRF more difficult.

Initial examination and reduction of impact excitation produced FRFs for frequencies less than approximately 15 Hz indicate damping values to be considerably greater than those for modes with frequencies greater than 15 Hz. The reason for this apparent damping increase for lower frequencies is not obvious until corresponding FRFs derived from shaker excitation are compared. It is seen that single modes in the impact FRFs are, in fact, two or more closely spaced modes as derived from shaker derived FRFs. The reason for this FRF difference for frequencies less than 15 Hz is due to loss of resolution in impact FRFs for this frequency range. Therefore, damping values, as derived from impact produced FRFs in the frequency range 1 through approximately 15 Hz, are belived to be invalid and are not reported herein.

The observed coherence roll-off for low frequencies is attributed to relatively low energy input for these frequencies considering the large mass and stiffness of the SCV. Coherence could be theoretically increased through increasing the number of acceleration samples taken for each FRF determination. However, a practical maximum number of averages is used in the present study.

4.2 Frequency-Damping Results

Due to the physical characteristics of the SCV, a large number of relatively uniformly distributed modes exist. Simple closed form calculations indicate that approximately 200 shell modes exist in the frequency range 1 through 33 Hz. Examination of FRFs obtained for both shaker and impact excitation reveal this characteristic as well. For this reason, no attempt is made herein to catalogue all modes indicated by the FRFs. Rather, frequency and damping determinations are performed for the major indicated modes and a relatively uniform distribution of reported mode frequencies in the range 1 through 33 Hz is presented. Where possible, two or more frequency and damping calculations are performed for the same mode using independent FRFs. In particular, it is felt that comparisons of frequency and damping for a given mode obtained from both impact and shaker test techniques are highly useful.

Frequency, damping, and mode numbering for all complex exponential curve fit results are presented in Table I. These results are graphically represented in Figure 5 as damping vs. frequency. Again, it is emphasized that the results presented herein do not represent an exhaustive catalogue of all modes present in the SCV.

Examination of Table I and Figure 5 indicate that there is no significant trend or difference between damping values derived from either impact or shaker excitation. However, one should not draw conclusions with respect to damping as a function of excitation energy since both excitation methods used herein are actually low energy methods when the extremely large mass and stiffness of the SCV is considered.

In addition, it may be seen from Figure 5 that damping is scattered over a relatively wide band. It is also observed that both upper and lower limits of this band increase with decreasing frequency. Thus, if a least squares second order curve would be fit through the data, one would observe a definite inverse relationship between damping and frequency which could be interpreted as a physical characteristic of the structure. However, due to the relatively flat lower scatter limit and observed difficulty with lower frequency FRF resolution, increased scatter and, hence, greater average damping values for lower frequencies could be attributed to test method applicability questions and/or difficulties with data reduction techniques.

4.3 Mode Shapes

Representative mode shapes of the SCV are tabulated in Table II. These mode shapes were derived from transfer functions using random input. They are not all the mode shapes calculated from the transfer functions but they represent the various kinds of general modes found in the structure. The modal response of the structure tends to have several general structure modes each with a variety of closely spaced shell modes. Thus, there is a range of resonant frequencies which display the same general response with differing localized shell response.

The global coordinate axes used for this test analysis are the $\bar{Z}$ axis extending from the center of the SCV towards the centerline of the materials hatch and the $\bar{Y}$ axis extending upwards. Global response of the SCV shell and dome with exception of torsion and the vertical dome modes consisted of motion primarily in the $\bar{X}$ direction. Apparently, the shaker, which was oriented in the $\bar{X}$ direction at the materials hatch, could excite shell modes in the cylinder but may not have provided sufficient energy input to excite any general response of the SCV in the $\bar{Z}$ direction.

5. Conclusions

The steel containment vessel data analysis provided modal damping and mode shape results from which to draw the following conclusions:

1. The vessel has a large number of uniformly distributed frequencies over the range of 1-33 Hz with damping levels approximately 2-4% of critical.
2. A trend towards average damping varying inversely with modal frequency is established.
3. The modal response of the SCV shows the structure to be quite complicated in its behavior. A number of the mode shapes are complex which indicate nonproportional damping is present.
4. General or global response of the structure is indicated in discrete frequency ranges. In each range there are several modes in which the global structural motion is coupled with local shell motion.
5. Only significant global response in one direction (that parallel to the shaker excitation) was perceived in the response functions. Even though energy input was sufficient for radial shell response, it was apparently not enough for any global response perpendicular to the shaker.

TABLE I. SCV MODES, FREQUENCIES, AND DAMPING

		Shaker Tests		Impact Tests	
Mode No.	Frequency (Hz)	Damping (% Critical)	FRF Used	Damping (% Critical)	FRF Used
1	1.74	2.08	1Y + (SS)[a]		
2	2.57	1.83	1Y + (SS)		
3	3.35	3.94	26Y +		
4	4.44	1.94	1Y + (SS)		
5	4.77	2.92	1Y + (SS)		
6	6.34	1.75	1Y + (SS)		
7	7.51	3.47	21Y +		
7	7.51	2.34	21X +		
8	8.02	2.72	21X +		
8	8.02	3.07	21Y +		
9	8.89	2.25	26Y +		
9	8.89	2.79	1X -		
10	9.14	2.48	21Y +		
10	9.14	3.42	1X -		
11	10.38	2.46	21X +		
12	12.25	2.47	21Y +		
13	13.74			3.34	30X -
14	14.78	2.75	1X -		
15	17.64	1.87	26X +		
16	19.74	2.96	21X +	3.31	20X -
16	19.74	1.97	26X +	2.79	26X -
17	21.18	2.11	1X -	2.03	30X -
18	23.90	2.36	26X +	2.83	15X -
18	23.90			2.25	30X -
19	27.21			2.85	15X -
19	27.21			2.49	32X -
20	28.30	2.45	21Y +		
20	28.30	1.57	26X +		
21	29.58			2.27	27X -
21	29.58			2.13	20X -
22	32.15	2.08	21X +	1.53	20X -
22	32.15			1.96	27X -
23	33.44	1.47	26X +	1.74	15X -
23	33.44			2.16	20X -

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a. (SS) indicates sine sweep derived FRF.

TABLE II. SCV MODE SHAPES

Mode Designation	Frequency Range of General Mode (Hz)	Representative Mode Frequency (Hz)	General Description of Modes in Frequency Range
A	7.47-9.25	8.85	Rigid body translation of upper head in $\overline{X}$ direction with various shell motion in cylinder.
B	10.38	10.38	Flexing of upper head in horizontal direction about 30° off the $\overline{X}$-axis with shell motion in cylinder
C	12.25-12.75	12.75	Cylinder ovalization at 30 m level with some translation of upper head in $\overline{X}$ direction
D	14.88-23.72	19.74	Torsion of cylinder and lower head with various shell motion in cylinder
E	28.10-28.79	28.30	Excitation of crane and girder mass driving shell in $\overline{X}$ direction
F	35.97	35.97	Vertical motion of dome center with shell motion in cylinder

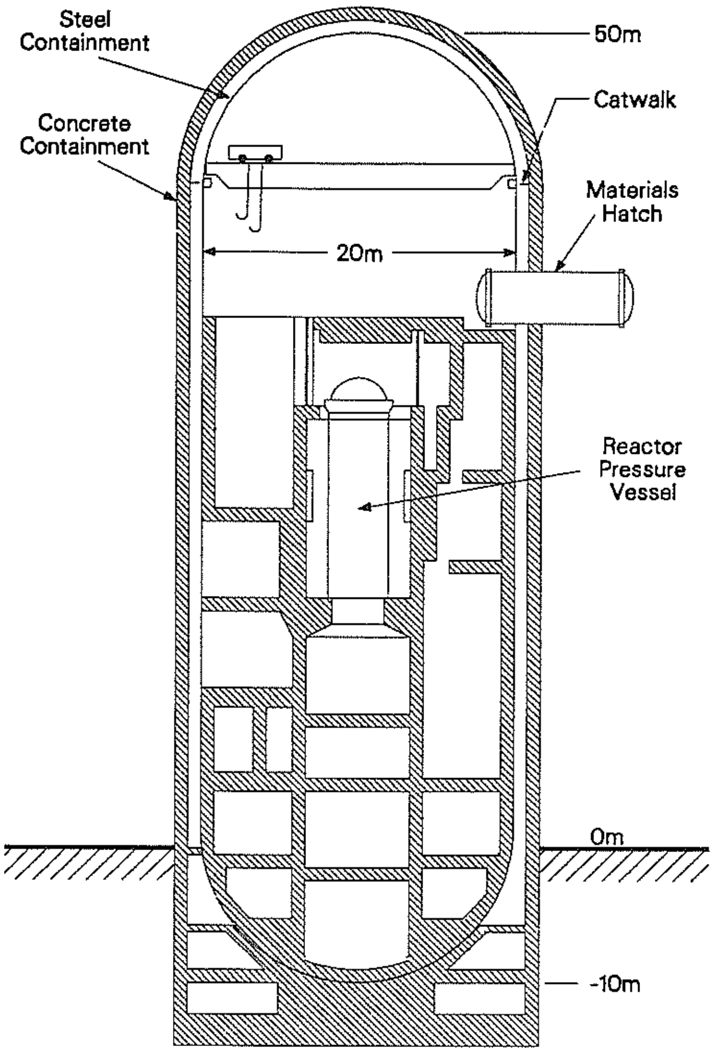

Figure 1. HDR containment cross section

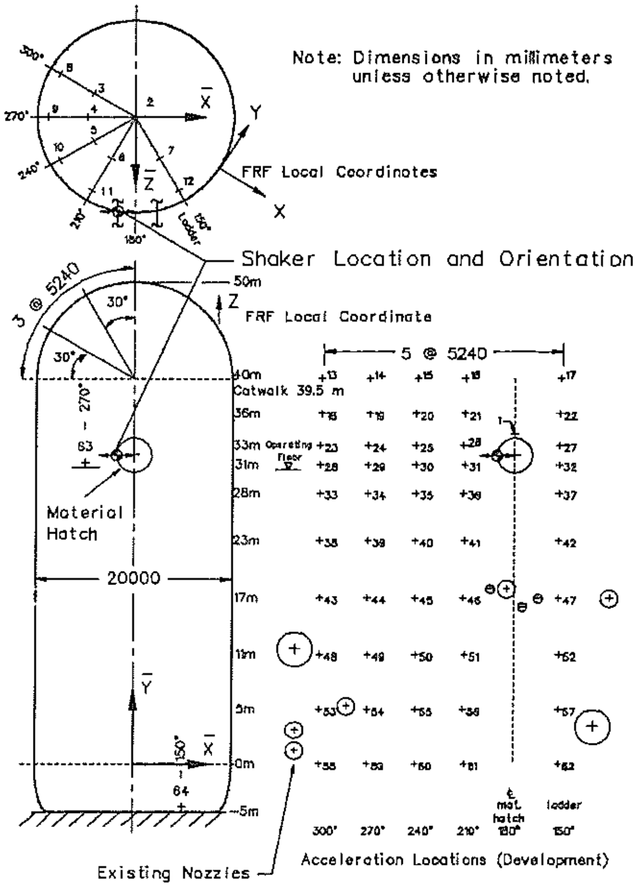

Figure 2. SCV geometry and instrument grid

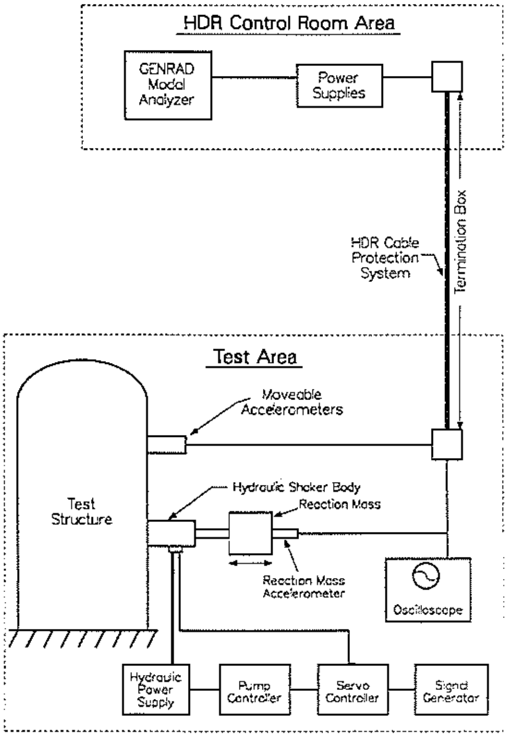

Figure 3. Hydraulic shaker test setup schematic

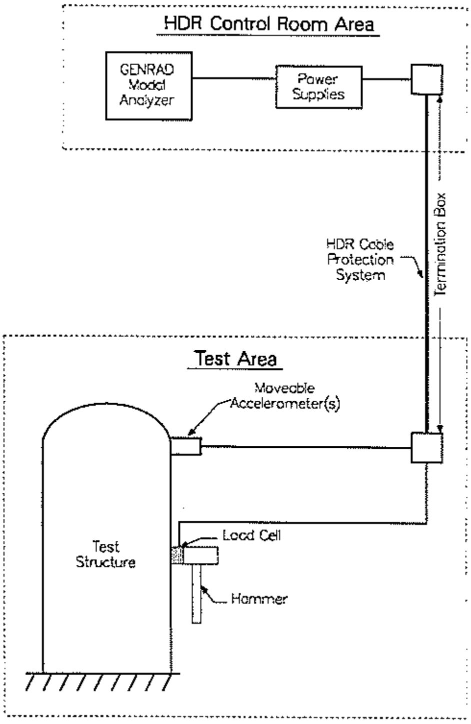

Figure 4. Impact test setup schematic

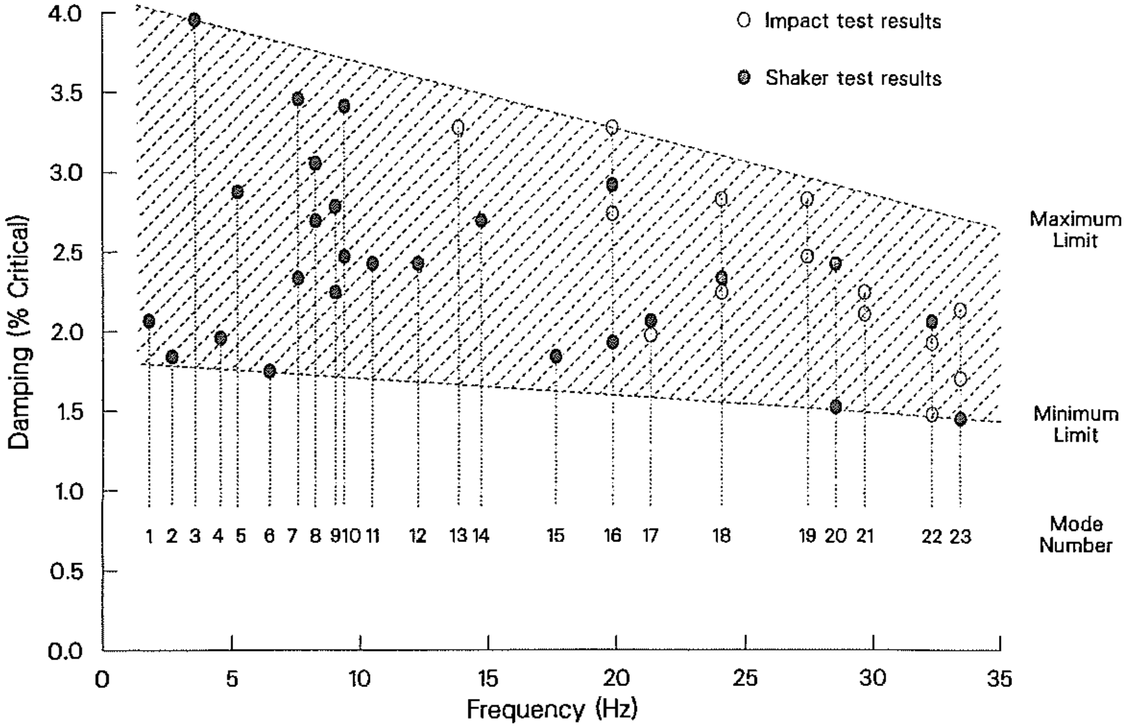

Figure 5. SCV damping vs. frequency