HDR Flood Water Storage Tank Modal Vibration Tests

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SUMMARY

Modal vibration tests were conducted by EG&G Idaho on two vessels located at West Germany's Heissdampfreaktor (HDR) facility which is 25 kilometers east of Frankfurt. The tests were performed during May and June 1982 for the U.S. Nuclear Regulatory Commission (NRC) as part of their cooperative effort with Kernforschungszentrum Karlsruhe (KfK) of West Germany. The primary purpose for performing this task was to determine modal properties (frequencies, mode shapes and associated damping ratios) in order to eventually provide guidelines for standards development by the NRC in modeling similar vessels.

One of the vessels tested was a flood water storage tank (FWST) for empty, half full and full water conditions. The FWST was excited randomly with an electromagnetic shaker and by impulsive hammer blows. Excitation or input forces together with measured vessel responses were processed by a digital modal analyzer and stored on magnetic disks for subsequent evaluation.

Analysis of the modal properties of the FWST resulted in the following conclusions:

1. The tank is very lightly damped with values generally less than 1% in the frequency response range of 2-40 Hz.
2. Modal damping, in general, is inversely proportional to frequency.
3. No significant increase in modal damping was observed as the water level in the tank ranged from empty to full.
4. Water mass in the tank affected the overall bending modes by reducing those natural frequencies while such mass was virtually uncoupled for the torsional modes of the tank.
5. A slight shift to higher natural frequencies of the torsional modes as the water level in the tank was increased might indicate pressure stiffening effects of the lower head of the tank.

Work supported by the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research under Interagency Agreement DOE 10-550-75 with the U.S. Department of Energy.

1. Introduction

The Federal Republic of Germany's Heissdampfreaktor (HDR) facility is a decommissioned superheated steam nuclear plant located 25 kilometers east of Frankfurt. Because of its similarity in size to commercial nuclear power plants in other countries, it has provided a viable "test bed" for numerous experiments which are of interest to many. As such, the U.S. Nuclear Regulatory Commission (NRC) sponsored, in cooperation with Kernforschungszentrum Karlsruhe (KfK) [1] of the FRG, modal vibration tests of two HDR vessels of which the flood water storage tank (FWST) is reported herein.

The objective of the tests was to determine the modal parameters (frequencies, mode shapes and associated damping ratios) of the tank for empty, half full and full conditions using two different test methods for comparative purposes. Results of these tests will be compared to previous tests [2, 3], and analytical predictions currently in progress to aid the NRC in developing standards for modeling such vessels. Ultimately, the "bottom line" is -- "How well can one analytically predict the behavior of similar structures?"

2. Test Vessel Description

The FWST shown in Figure 1 is a carbon steel tank located in the process building with four similar tanks. This vertically oriented 90,000 l capacity tank has an overall height of 12 m, a 3.3 m diameter, and a shell thickness of 12 mm. The tank is supported at the lower head by a welded box-shaped pedestal and four short steel I-beam columns which are bolted to the pedestal and floor.

All piping nozzle attachments to the tank are located either on the top or bottom head of the tank. Inlet and drain line nozzles are located inside the box pedestal at the bottom. A vent tube is located on the inside of the tank running vertically upward from the bottom along its axis, out the top and down the outside of the shell. This vent line is clamped at several locations to anchor blocks which are welded to the shell of the tank. One other pipe line normally joins the tank on the top head but was disconnected at the bolted flange for the duration of the tests. A manhole is also located in the top head for entering the tank for maintenance purposes.

3. Test Description

3.1 Tank Geometry

The test response measurement locations selected for the tests are also illustrated in Figure 1. They consist of 30 points on the cylinder and 1 point on the manhole nozzle cover. For each point on the cylinder both radial and tangential (horizontal) response components were measured. Thus 61 response components or spatial coordinates were considered.

For the tests described below, three sets of tests were run with the water level in the tank set at empty, half full and full, respectively.

3.2 Shaker Tests

For random noise input shaker tests the tank was excited horizontally at the manhole cover by a 445 N electrodynamic shaker as depicted in Figure 1. Figure 2 shows the actual installation wherein the shaker base is anchored to a nearby wall and its moveable head is connected to the tank via a force link (load cell). As noted from the figures, the shaker was oriented at a 45^0 angle (measured horizontally from the wall) to impose both bending and torsional motion of the tank.

Response of the tank was measured with a set of six accelerometers which were moved from point to point on the tank until data had been collected at all designated locations. To facilitate the data acquisition process, the accelerometers (oriented to measure radial and tangential response) were mounted in pairs to three magnetic bases for easy vessel attachment and removal. Input forces were continuously monitored by an oscilloscope to assure adequate yet safe input. Figure 3 shows a schematic of the test setup.

3.3 Impact Tests

The tank was excited for impact tests by striking it with a hammer radially at each designated location on the tank. A number of impact tests were made at each location to allow averaging of the response to reduce any noise effects in the data. The response was measured with a radially oriented reference accelerometer located at a fixed response location on the shell. Since these tests were insufficient to excite the torsional modes, an additional set of tests was performed. For this set of tests, the hammer was used to torsionally excite the tank by striking the manhole nozzle horizontally in the X direction and measuring tangential responses at each location along column line "D" as shown in Figure 1.

3.4 Data Acquisition

For all tests, the input forces and response accelerations were transmitted via a three part cabline system to the modal analyzer located in a room adjoining the HDR control room. The first part of the cabling system transmitted signals from the transducers to a central HDR cable termination box located near the vessel. Next, the signals were transmitted through HDR's cable protection system to a termination box outside the control room. Finally, signals were transmitted via cables to the 8 channel GenRad 2508 modal analyzer.

DATM [4] software was used for the data acquisition phase of the project. For frequency response function (FRF) estimation during the random shaker tests, the anti-aliasing filters were initially set at 50 Hz with the low pass random excitation filter set at 100 Hz. For identified frequency ranges of major response, additional random tests were performed to "zoom", or evaluate with higher resolution, those frequency ranges. These "zoom" tests involved considerably longer acquisition times than the initial baseband tests. The number of averages taken for each baseband test was 120 while 70 was taken for the "zoom" tests. A Hanning window was employed for both tests to enhance the response data by minimizing the "leakage" normally associated with periodic functions.

DATM software was also used for the impact tests. The anti-aliasing filters were also set at 50 Hz but only 20 averages were taken per response location. An exponential window was employed during these tests to assure that the response died out within the time record. This in effect introduces artificial damping into the system which has to be later compensated for in the data reduction process.

3.5 Data Reduction

MODAL-PLUS [5] software was used to extract the modal parameters from the FRF data obtained during the tests. The general procedure used to obtain the parameters is summarized as follows:

1. Define the spatial geometry of the test grid
2. Examine FRFs for well defined resonances, coherence, and phase
3. Select FRFs to be used for determination of parameters

4. Perform multi-degree-of-freedom (MDOF) complex exponential curve fit of each selected FRF

5. Adjust damping values for any artificial damping added during data acquisition

6. Determine frequency dependent mode shape coefficients for each degree-of-freedom (DOF) in the test grid from each FRF in a given test group

7. Transform mode coefficients from local to global coordinates

8. Evaluate mode shapes using various static and animated graphic displays.

4. Test Results

Figure 4 shows a typical FRF obtained during shaker excitation tests with the tank empty. As can be seen there are three large peaks and several smaller magnitude peaks. The larger peaks are associated with overall rocking and torsion of the tank. The smaller ones represent, for the most part, shell modes. The peak near 4 Hz is actually two closely coupled first rocking modes of the tank. Table I lists the modes associated with the larger peaks for empty, half full and full water conditions of the tank. As noted, the rocking mode frequencies of the tank decrease as expected and the two lowest mode frequencies become nearly equal in value when the water level is increased. The torsional modes, however, increase slightly with increased water level. The reason for the shift is not completely understood. However, it is suspected that this phenomenon is caused by pressure stiffening of the bottom head due to the increased mass of the water and other peculiarities of the support. It also indicates that the water mass is virtually uncoupled from the tank in torsion. Measured damping values for the shaker tests were quite low ($<1.1\%$ of critical) and showed, with the exception of a few points, an inverse relationship between frequency and damping as shown in Figure 5. Figure 6 shows the first bending, first torque, and second bending mode shapes for the empty tank. Similar mode shape results were obtained for the other water levels of the tank.

Impact test results are not reported herein as similar results were obtained, especially for frequencies and damping. Extraction of the mode shapes were more difficult to obtain than for the shaker tests because the FRFs were more erratic.

A discussion of test results would not be complete without some evaluation of the quality of the recorded data. The basic components of this test analysis are the frequency response functions or transfer functions. Quality of these functions is determined by their coherence and resolution.

During all the tests on the tank, ambient noise was emanating from heavy machinery which needed to be operated continuously for plant operation. The shell response from this noise was large enough to be felt by placing a hand on the tank's surface. This created a less than optimum signal to noise ratio in the data for all tests. For this reason the general quality of the coherence functions corresponding to the regular transfer functions of random input is not as good as the goal set (≥ 0.9) in the test plan [6]. However, this does not necessarily mean that these transfer functions are invalid, especially if the extraneous input can be characterized as white noise in the frequency range of concern. Inspection of the power spectral density function of the tank showed the background noise level to be flat over the frequency range of interest. The coherence functions also indicate a varying lower frequency limit of reliability of the random input functions for the various water levels in the tank. This is due primarily to the energy input limited by displacement of the electromagnetic shaker used in the random tests. This lower limit ranges from 2-3 Hz for the empty condition in both radial and tangential responses, 2-3 Hz in tangential response for the half full condition, and 10-15 Hz in tangential response for full condition. The coherence functions for impact hammer data, however, are good down to about 1 Hz.

Resolution of the baseband random input FRFs was not as good as the zoomed data and was evident in the inability to determine some very closely spaced modes. For this reason the most accurate damping data for this structure was determined from the zoomed functions.

5. Conclusions

The FWST is a very lightly damped structure with a rather flexible support. The structure has a number of shell, torsional, and rocking modes within the frequency range of seismic concern. Damping for the structure generally varies inversely with frequency. The mass of water in the tank affected the rocking modes of the structure by reducing their natural frequency. A slight shift to higher natural frequencies of the torsional modes indicates the water mass to be essentially uncoupled from the shell in those modes and also a possible pressure stiffening effect of the bottom head.

References

[1] HDR-Safety Program-General Program-Status as of June 1980, Kernforschungszentrum Karlsruhe GmbH, May 1981.

[2] Erdbebenuntersuchungen am Heissdampfreaktor in Kahl; Shakerversuche auf mittlerer und hoher Anregungsstufe, KfK, Projekt HDR-Sicherheitsprogramm, Quick Look Report Versuchsgruppe V. 63 PHDR 13-8--in Vorbereitung.

[3] STEINHILBER, H., RESCH, W., Versuch mit Impulsanregung eines Flutwasserbehälters am HDR, BF-R-63.929-1, April 1981.

[4] DATM User Manual, Version 6.0, Structural Dynamics Research Corporation, June 1981.

[5] MODAL-PLUS User Manual, Version 6.0, Structural Dynamics Research Corporation, August 1981.

[6] ARENDTS, J. et al., Dynamic Tests on HDR Flood Water Storage Tank (V69) and HDR Steel Containment Vessel (V70), Design Report, PHDR Internal Report 4.212/82, June 1, 1982.

Table I

FWST MODAL PARAMETERS

EMPTY		HALF FULL		FULL		
Frequency (Hz)	Damping (% Critical)	Frequency (Hz)	Damping (% Critical)	Frequency (Hz)	Damping (% Critical)	Mode Description
4.0	0.5	3.2	0.6	1.7	0.6[a]	First bending
4.3	0.3	3.3	0.6	1.7	0.6[a]	First bending
41.3	1.1	24.4	0.3	18.7	0.9	Second bending
22.3	0.3	25.2	0.2	25.8	0.2	First torque

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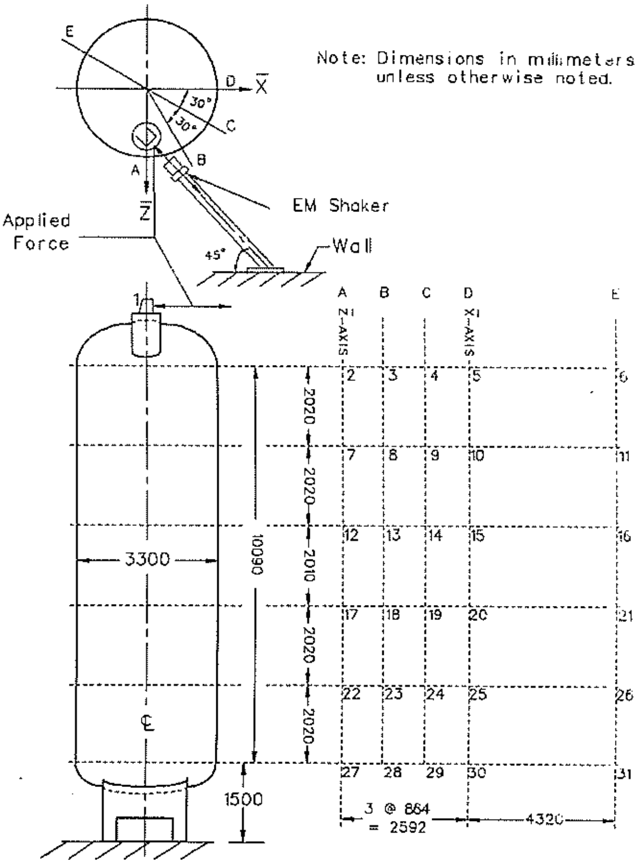
a. estimated



Note: Dimensions in millimeters unless otherwise noted.

Figure 1. FWST geometry and instrument grid

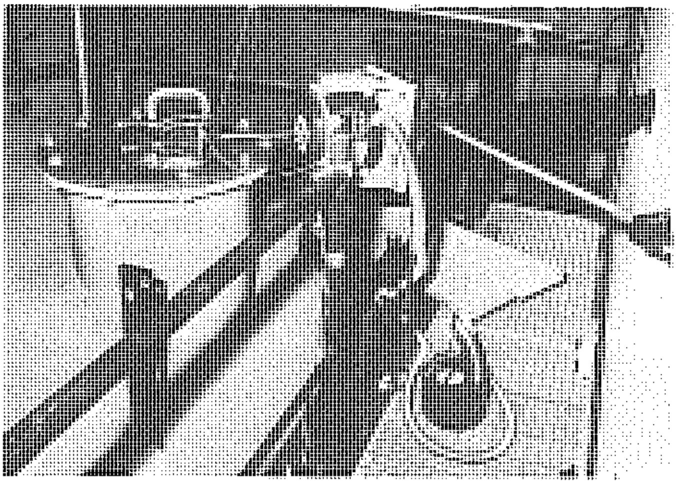


Figure 2. Electromagnetic shaker test setup

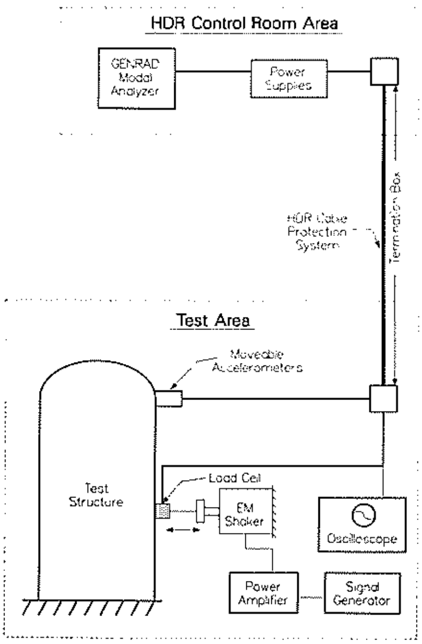


Figure 3. Test instrumentation setup

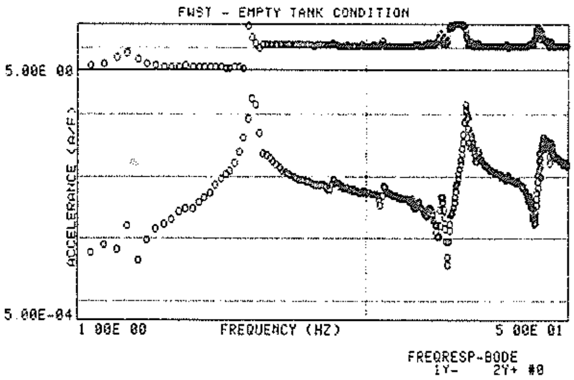


Figure 4. Baseband frequency response function

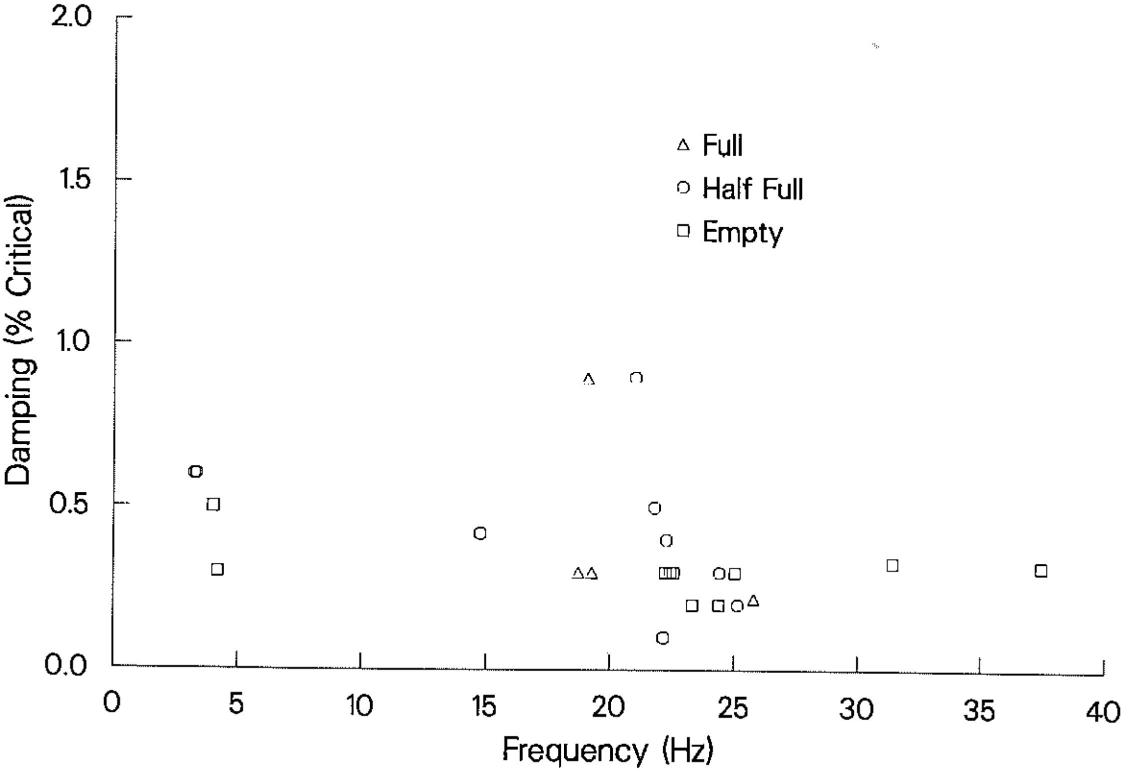
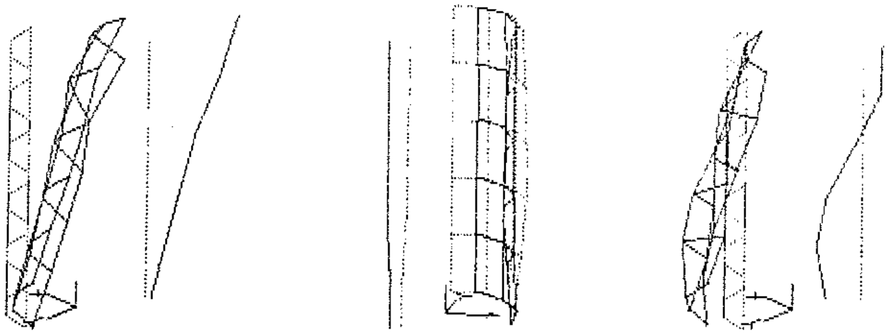


Figure 5. Damping vs. frequency



(a)
First bending
4.0 Hz

(b)
First torque
22.3 Hz

(c)
Second bending
41.3 Hz

Figure 6. Mode shapes for empty FWST