EXPERIMENTAL INVESTIGATIONS OF NATURAL FREQUENCIES AND MODES OF THE HDR NUCLEAR POWER PLANT BY MEANS OF MICROTREMOR EXCITATION

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SUMMARY

This paper outlines the experimental investigations of natural frequencies and modes of the HDR nuclear power plant in Kahl/Main Germany. The method presented requires excitation only by natural microtremors, wind loading, traffic and so on, so that no artificial excitation is necessary. The theoretical background of the procedure is delineated and results of measurements at the HDR are given and compared with results gained by other methods.

INTRODUCTION

Natural microtremors occur at any site and at any time, so that it seems reasonable to use them for excitation of buildings to obtain natural frequencies and modes. Beneath the microtremor excitation, wind excitation and excitation by traffic and similar sources - described in short as "environmental noise" is also present exciting different types of buildings. To detect natural frequencies and modes using this kind of excitation it is necessary to use high sensitivity recorders such as portable seismometers working even at low frequencies down to approximately 0.1 Hz.

To develop a method for measuring frequencies and modes of buildings it is only necessary to have in addition to these seismometers, a spectrum analyzer equipped with modal analysis software. The method described here was previously successful in detecting natural frequencies and modes of highrise buildings (Ref. 1,2) under the effect of wind as well as microtremor excitation. Now it has been used to determine the dynamic behaviour of such a comparatively rigid structure as a nuclear power plant, where we believe that microtremor excitation is the major factor. The procedure is based on the assumption that environmental noise, and therefore the excitation function, can be considered as a stationary ergodic stochastic process. By analyzing the time history signals of a suitable length received from the seismometers, every desired mode up to about 30 to 50 Hz and the corresponding natural frequency can be determined.

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The advantage of the method is that no artificial excitation is necessary, so that measurements can be performed on completed buildings in full use without any damage and without having to interrupt work, as well as on structures in any stage of completion. It is of utmost importance to be able to check calculations of the vibration behaviour in order to ensure the earthquake resistance of the structure.

The investigations were made within the HDR safety program which includes several investigation projects to determine the structural behaviour of reactor building and reactor containing vessel as well as of tanks and piping systems with respect to seismic response analysis. All the projects are related to the HDR facility in Kahl/Main Germany, an inactive nuclear power plant now used for several kinds of experiments.

PERFORMANCE OF VIBRATION MEASUREMENTS

Experimental Facilities

9 Willmore system portable seismometers with a natural frequency of 1 Hz and a sensitivity of 4 Volt.s/cm were used. Their working range is down to approximately 0.1 Hz. The instruments available were sufficient to obtain synchronous time records for 3 points in 3 directions each. The time history records of the velocities were stored by a 14-channel Sabre VII tape-recorder system. The signal of one direction of one of the 3 points was taken as a reference. A single synchronous measurement consists of a three-point ensemble whereby the results of all measurements taken have to be superimposed during the analyzing-procedure. Due to the assumption that the excitation is a stationary stochastic process, the individual measurements can be made one after the other by moving the measuring equipment to places distributed throughout the building. To neutralize random variations in the excitation level it is necessary to receive the time history signals for a long enough time. A measuring period of approximately 40 minutes was used for a single measurement. This has proved to be reasonable.

Analyzing Procedure

The time history signals were processed by an HP 5423A Modal Analyzer which computes the transfer functions from the Fourier transforms of the time history signals in each direction at each point with respect to the Fourier transform of the reference signal. The power spectral densities of the signals, which are also available from the analyzer, allow the determination of natural frequencies. The computing of the mode shape is performed in the analyzer by assuming each degree of freedom (DOF) of the system to be a single-DOF-system. More convenient processing and the adjustment of the system measured to a multi-DOF-model would yield a little more accuracy and reduce processing time, but on the other hand would require more expensive equipment.

THEORETICAL BACKGROUND

Applying Fourier transformation to an oscillating linear mechanical system with n DOF yields in the frequency domain (Ref. 3) the equation

$$(1) \qquad \sum_{k=1}^{n} B_{jk}(i\omega)\, X_k^a(i\omega) = X_j^e(i\omega) \qquad j = 1,..,n$$

where B_{jk} is given by

$$(2) \quad B_{jk}(i\omega) = -\omega^2\delta_{jk} + i\omega\sum_{l=1}^{n} m_{jl}^{-1} d_{lk} + \sum_{l=1}^{n} m_{jl}^{-1} c_{lk}$$

In eq. (1) and (2) B_{jk} is the "system matrix", X_j^e is the Fourier transform of the input which is here the specific excitation time history function at point j, X_k^a is the Fourier transform of the output, here the time history function of the displacements of the system at point k, $x_k(t)$, with time t. The argument ω is the variable in the frequency domain with the imaginary unit i. The system matrix B_{jk} consists according to eq. (2) of 3 terms; the first contains the unit matrix δ_{jk}, the second one the damping matrix d_{lk} and the third one the stiffness matrix c_{lk} of the system, whereby the latter two are premultiplied with the inverse of the mass matrix m_{jl}. It is assumed here that the structure of the damping matrix is such as to produce a diagonal matrix shape when orthogonally transformed by means of the modal matrix of the system, that is the matrix of the mode shapes.

The inverse matrix of the system matrix B_{jk} is known as the "transfer matrix" or the matrix of transfer functions G_{jk}. It follows from eq. (1):

$$(3) \quad X_j^a(i\omega) = \sum_{k=1}^{n} G_{jk}(i\omega)\, X_k^e(i\omega) \qquad j = 1,..n$$

To determine the mode shapes as well as the modal damping of the system investigated, it is sufficient to know one row or column of the transfer matrix G_{jk}, Richardson and Potter (Ref. 4). Measured time-history-signals of the displacements $x_k(t)$ can be transformed into the frequency domain by the "Fast Fourier Transform" (FFT). From these transformed values the elements of the transfer matrix can be calculated according to

$$(4) \quad G_{jk} = X_j^a \,/\, X_k^e$$

In the actual case the time history functions are not displacements but velocities, but it is clear from eq. (4) that this makes no difference for the transfer function provided that input and output are of the same character. This is the case when the output signal comes from the measuring point, the input signal from the reference point.

To obtain the natural frequencies of the system investigated, the power spectral densities of input and output signals are required, which are defined according to

$$(5) \quad S^e_{x_k x_m}(\omega) = X_k^e(i\omega)\, X_m^e(-i\omega) \qquad \text{and}$$

$$(6) \quad S^a_{x_j x_l}(\omega) = X_j^a(i\omega)\, X_l^a(-i\omega)$$

for input and output respectively. In accordance with eq. (3), the relation between the two power spectral density matrices is given by

$$(7)\qquad S^{a}_{x_j x_l}(\omega) = \sum_{k,m=1}^{n} G_{jk}(i\omega)\; G_{lm}(-i\omega)\; S^{e}_{x_k x_m}(\omega).$$

If the power spectral density of the input is taken to be "white noise" as assumed above, it is constant with respect to ω and can be written as

$$(8)\qquad S^{e}_{x_k x_m}(\omega) = C_k \delta_{km}$$

with a calibration constant C_k. Inserting eq. (8) into eq. (7) yields

$$(9)\qquad S^{a}_{x_j x_l}(\omega) = \sum_{k=1}^{n} G_{jk}(i\omega)\; G_{lk}(-i\omega) C_k,$$

which means that the Power spectral densities of the output are given essentially by the transfer functions. If there is only one point k at which the excitation acts, one row and one column of the transfer matrix are sufficient to obtain the power spectral densities of the output. The peaks of these functions with the same indices, the "autospectral densities", represent the natural frequencies of the system.

RESULTS OF THE INVESTIGATIONS AT HDR NUCLEAR POWER PLANT

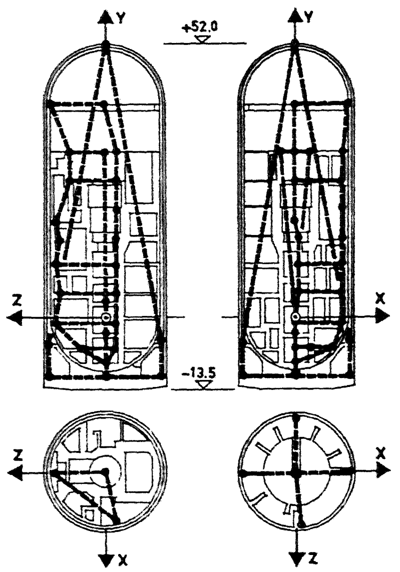


Fig. 1: HDR Nuclear Power Plant Measuring Points with Grids in Plans and Elevations.

The HDR is shown in figure 1 in plans and elevations with grids connecting the measuring points used (their numbers are given in figure 2). The power plant consists of an outer circular cylindrical concrete shell with a domed top, and an inner steel case containing the concrete structure of the actual power plant with the containing vessel and so on. Both parts of the building are jointly situated on a common foundation-plate.

The table shows the natural frequencies and damping values determined, in comparison with results of measurements made with artificial excitation which are published in references 5 and 6. It is clear from this comparison that all frequencies detected by artificial excitation are also determined by the method described here. The damping values - if given - vary with different measurements and are considered to give the accurate order of magnitude. The frequency values are mean values of about half of all measurements. The table contains only the dominant values concerned with the plant as a whole.

TABLE OF THE NATURAL FREQUENCIES DETERMINED

Mode Nr.	Presented method Frequency Hz	Damping %	Reference 5 Frequency Hz	Reference 6 Frequency Hz
1 A	1.490	3.89	1.52 -	1.35 - 1.48
1 B	1.526	3.89	- 1.57	1.40 - 1.54
2 A	2.563	2.49	2.63 -	2.44 - 2.53
2 B	2.625	3.35	- 2.81	2.56 - 2.66
3	3.352	1.94	3.35	
4	4.561	0.58		
5	5.059	0.35		4.98 - 5.00
6	5.165	1.58		
7	5.843	-		5.70 - 5.90
8	6.553	1.03		6.32 - 6.54
9	7.192	0.65		7.32
10	7.832	0.37		7.80
11	8.104	0.47	8.16	
12	8.844	0.32		8.50
13	9.750	0.21		
14	11.341	-		11.36 - 11.58
15	12.410	0.24	12.25	
16	13.281	0.15	12.80	13.00 - 13.22
17	13.980	0.13	13.88	
18	14.421	0.15	14.60	14.20
19	14.832	0.53		
20	15.033	0.48		15.07 -
21	15.346	0.21	15.25	- 15.26
22	15.863	0.34		
23	16.500	0.37		
24	17.416	0.07		
25	20.000	0.10	20.00	
26	23.465	0.11		
27	23.761	0.11		
28	24.666	-	24.50	
29	26.031	0.11		
30	28.906	-	29.00	
31	29.805	0.28		
32	31.975	-		

Figure 2 shows the undeformed state of the grids connecting the measuring points of two components: Component 1 represents the outer shell structure, component 2 the inner structure. The figures inserted are the numbers of the measuring points. In the upper region of the outer shell only one point at the top of the dome could be used as the walls of the outer cylinder were inaccessible.

Figure 3 shows the power spectral densities of horizontal and vertical velocity at point 26, that is the lowest point measured in the center of the foundation-plate. These graphs support the assumption of the white-noise-character of the excitation, although they are influenced by the building of course and contain the peaks of the plant. But a measure-

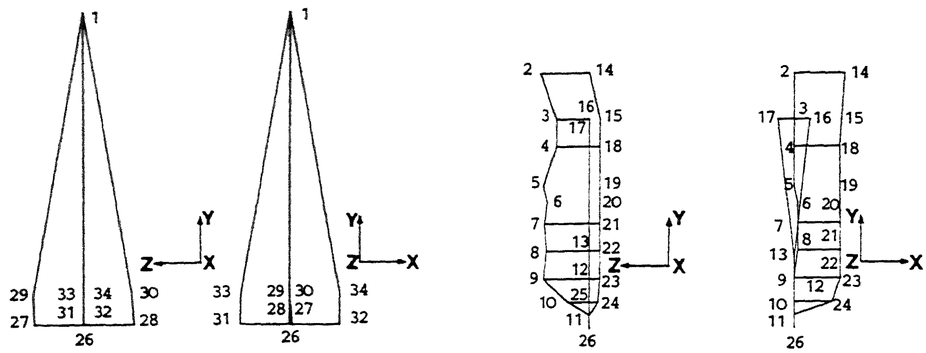


Fig. 2: Grids of the undeformed structure, component 1 and component 2 respectively with numbers of measuring points. For total views see figure 1

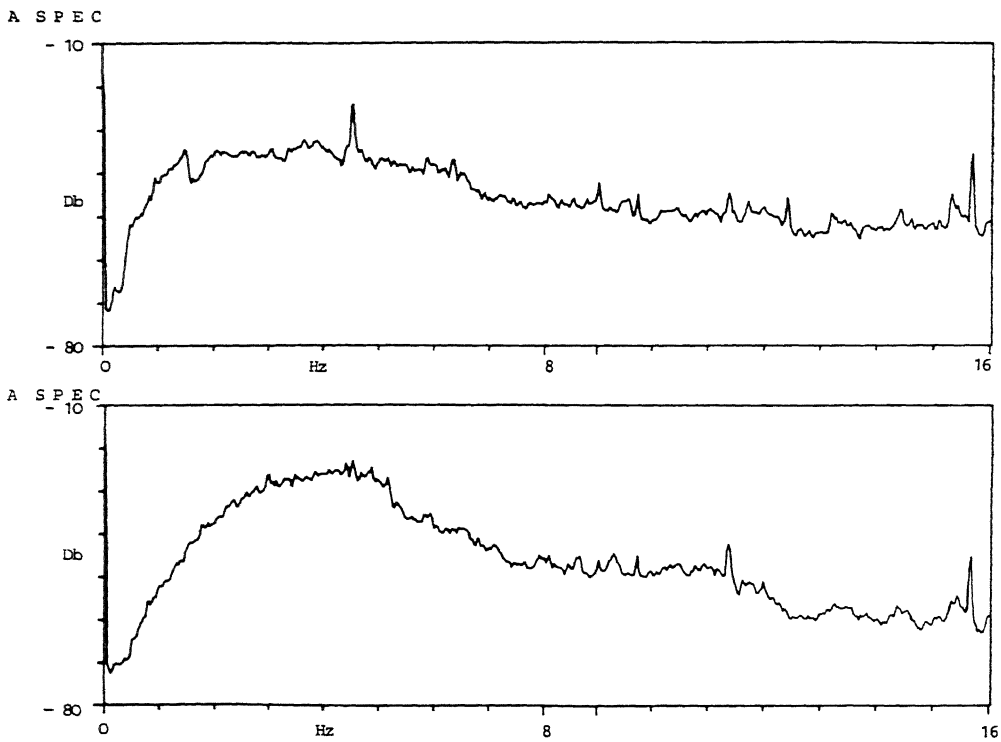


Fig 3: Power spectral densities of the velocity signals recorded at point 26, upper graph horizontal (z-direction) lower graph vertical velocities in the range from 0 to 16 Hz

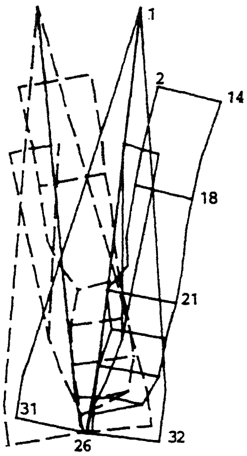


Fig. 4: Mode 1, a rocking mode of the whole building, 1.490 Hz, 1.526 Hz

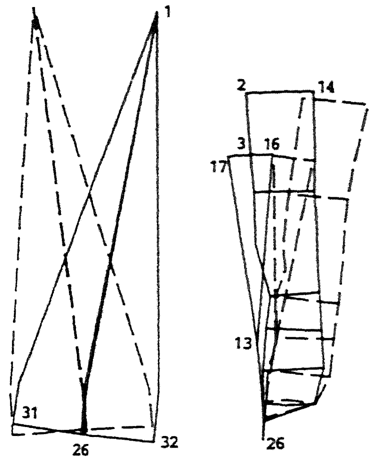
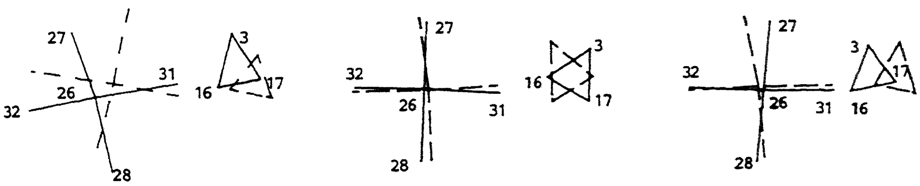


Fig. 5: Mode 2, counterphase oscillation of components 1 and 2, 2.563 Hz, 2.625 Hz



Mode 6
5,165 Hz

Mode 9
7,192 Hz

Mode 13
9,750 Hz

Fig. 6: Torsional modes, plans of components 1 and the upper parts of component 2, oscillating in phase (mode 6), only component 2 (mode 9) and in counterphase (mode 13)

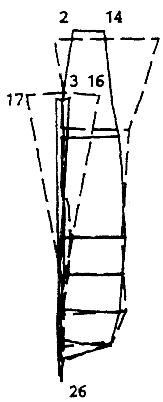


Fig. 7: Mode 27, an ovalling mode of the upper part of component 2, 23.761 Hz

ment about 20 m beneath the building - if possible - would show a more uniform excitation density certainly still containing the influences of the local boundary conditions in the ground of the region. Therefore the method could also be used to obtain groundspectra of a building site in order to detect the relative earthquake endangerment of a site before erecting the structure (Ref. 8).

Figures 4 to 7 show some selected mode shapes automatically drawn by the analyzer. The two positions shown, ohne in solid and the other in dotted lines are the two extreme situations when oscillating. For additional mode shapes see reference 3 and 7. In figure 6 for reasons of clearness only the foundation-plate (points 27, 28, 31 and 32) and a plane in the upper region of the inner structure (points 3, 16 and 17) are shown. As an example of a higher mode figure 7 shows an ovalling mode of the walls surrounding the containing vessel in the upper part of the inner structure.

More information that can be presented here can be extracted from the measurements available on tape. More measuring points than used here would give more detailed information with respect to the mode shapes. Further investigations are planned to detect the stochastic character of the micro-tremor excitation in order to develop optimal measuring conditions.

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