Identification of Natural Frequencies and Modes of a Nuclear Power Plant by Means of Excitation with Environment Noise

E. Luz, C. Gurr-Beyer, W. Stoecklin
Institut für Mechanik (Bauwesen), Universität Stuttgart, Postfach 80 11 40, D-7000 Stuttgart 80, Germany

A method is presented to detect natural frequencies and corresponding mode shapes of buildings excited by microtremors and environmental noise only. Theoretical considerations are made to substantiate the chosen procedure. The experimental facilities required for the method and their way of operation are delineated. Results of measurements at the HRD nuclear power plant at Kahl/Main, Germany are presented and compared with other measurements.

1. Introduction

The method presented was developed to determine natural frequencies and corresponding mode shapes of highrise buildings. As it is difficult to excite such buildings artificially, efforts were made to find instruments sensitive enough to detect the values required even at very low excitation levels - such as originate from microtremors, wind excitation and artificial tremors caused by cars, trains, machinery and so on - briefly called "environmental noise".

It was not clear from the beginning that this method, which has been applied very successfully to several highrise buildings, Luz and Gurr, [1] [2], would be verified in detecting frequencies and modes of such comparatively rigid structures as nuclear power plants. But now results of measurements at the HDR nuclear power plant at Kahl/Main, Germany - which is currently being used as a test object for nuclear safety research - are available and can be compared with results of measurements gained by higher and artificial excitation, Steinhilber, [3], Jehlicka, [4]. This comparison shows a good agreement and demonstrates that the method described here can be used to determine the dynamic behaviour of any kind of building.

The advantage of the method is that no artificial excitation is necessary, so that completed buildings which are in full use can be measured, without any damage and without having to interrupt other work, as well as structures in any state of completion. It is important to be able to check calculations of the dynamic behaviour of structures in an easy manner in order to ensure the earthquake resistance of the building. Further it is important to be able to check input data for the machinery and piping design of a power plant when the structure itself is completed and the technical equipment is not yet installed.

2. Measuring Method

2.1 Theoretical Background

An oscillating mechanical system with n degrees of freedom (DOF) and with damping is described by the system of differential equations in the time domain:

$$\sum_{k=1}^{n} (m_{jk}\ddot{x}_k + d_{jk}\dot{x}_k + c_{jk}x_k) = p_j(t), \qquad j=1...n, \qquad (1)$$

where $x_j = x_j(t)$ is the deformation vector of the system, m_{jk} its mass-matrix, d_{jk} the damping-matrix, c_{jk} the stiffness-matrix and $p_j(t)$ the excitation; t represents the time and dots derivatives with respect to t. The solution of eq. (1) is given by

$$x_j(t) = \sum_{k=1}^{n} \varkappa_{jk} A_k e^{-\delta_k t} \cos(\nu_k^D t - \varphi_k) + f_j^P(t), \; j=1...n, \qquad (2)$$

provided that the damping-matrix is to be uncoupled by the matrix $\varkappa_{jk}$ of the mode shapes, that means

$$\sum_{j,r=1}^{n} \varkappa_{jl}\, d_{jr}\, \varkappa_{rk} = D_{lk}, \qquad k,l = 1 \ldots n. \tag{3}$$

In eqs. (2) and (3) $\varkappa_{jk}$ is the matrix which consists of the k columns of the mode shapes in the undamped case, δ_k the k^{th} damping coefficient, ν_k^D the k^{th} damped angular frequency, A_k and φ_k the k^{th} amplitude and phase angle, to be determined according to the initial conditions, $f_j^p(t)$ a particular solution of eq. (2) depending on the excitation $p_j(t)$ and D_{lk} the diagonal matrix of modal damping. If the damping matrix d_{ij} does not fulfill eq. (3) the solution becomes more complicated, Luz [5], and hence also the analyzing procedure, to be described in section 2.2.2. It should be noted that the solution of eq. (1), eq. (2), contains every mode shape of the system oscillating with its natural frequency, ν_k^D.

Applying Fourier transform to eq. (1) previously multiplied with the inverse matrix of m_{jk} yields:

$$\sum_{k=1}^{n} (-\omega^2 \delta_{jk} + i\omega \sum_{l=1}^{n} \bar{m}_{jl}^{1} d_{lk} + \sum_{l=1}^{n} \bar{m}_{jl}^{1} c_{lk})\; X_k^a(i\omega) = X_j^e(i\omega) \tag{4}$$

with

$$\sum_{l=1}^{n} \bar{m}_{jl}^{1}\; P_l(i\omega) = X_j^e(i\omega), \qquad j = 1 \ldots n. \tag{5}$$

In eqs. (4) and (5) i is the imaginary unit, ω the variable of the frequency domain, $X_j^a(i\omega)$ the Fourier transform of the "output" $x_j(t)$, $P_l(i\omega)$ the Fourier transform of the excitation $p_l(t)$ and $X_j^e(i\omega)$ the Fourier transform of the "input" according to eq. (5). The matrix in brackets on the left hand side of eq. (4) is called the "system matrix", the inverse matrix of the system matrix is known as the "transfer matrix" or matrix of transfer functions $G_{jk}(i\omega)$. It follows from eq. (4):

$$X_j^a(i\omega) = \sum_{k=1}^{n} G_{jk}(i\omega) X_k^e(i\omega), \qquad j = 1 \ldots n. \tag{6}$$

To determine the mode shapes of the system it is sufficient to know a row or a column of the transfer matrix G_{jk}, Richardson and Potter [6].

The excitation of the structure by environmental noise is considered as a stationary ergodic stochastic process containing all frequencies with the same intensity, known as "white noise" in the frequency domain. In fact this is not true, but the white noise can be used as an approximation to the real behaviour of the character of excitation. Measured time-history-signals of deformations $x_j(t)$ - which are equivalent to $\dot{x}_j(t)$ and $\ddot{x}_j(t)$ - can be transformed into the frequency domain by "Fast-Fourier-Transformation" (FFT). From these transformed values the elements of the transfer matrix can be calculated according to

$$G_{jk} = X_j^a \,/\, X_k^e \tag{7}$$

for the k^{th} element of the input and the j^{th} element of the output.

2.2 Experimental Facilities and Performance of Measurements

2.2.1 Recording Equipment

The measuring method is based on the high sensitivity of the recorders used. These are Willmore system portable seismometers with a natural frequency of 1 Hz and a sensitivity of 4 Volt.s/cm. The working range is down to 0.1 Hz. There were 9 instruments available 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 measurement for one direction of one of the 3 points is to be taken as a reference. Each measurement performed consists of such three-point ensembles, whereby the results of all measurements taken have to be superimposed during the analyzing-procedure. Due to the assumption that the exciation is a stationary stochastic process, the single measurements can be made one after the other by moving the measuring places throughout the building. It is necessary to receive the time signals long enough to neutralize random variation in the excitation level. In this case a measuring time of approximately 40 minutes was used.

2.2.2 Analyzing Procedure

The analysis of the time history signals was performed by an HP 5423A Modal Analyzer which has been shown to be efficient enough to process the data measured. The instrument computes the transfer functions according to eq. (7) from the Fourier transforms of the signals of each direction at each point with respect to the reference signal and allows the determination of natural frequencies and modes. The computing of the mode shapes is performed by assuming each DOF to be a single-DOF-system. This sometimes causes difficulties in distinguishing modes with frequencies lying close together. But in principle, a larger scale analyzer would solve this problem.

3. Results of Measurements at HDR Nuclear Power Plant

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

The table shows the natural frequencies determined, in comparison with the results of measurements made with artificial excitation which are published in references [3] and [4]. It is clear from this comparison that all frequencies detected by artifical excitation are determined by the method described here too.

The undeformed state of the grid is shown in Fig. 2. Displayed are the grids connecting the measuring points of two components: Component 1 representing the outer shell structure, component 2 the inner structure. 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. Some selected mode shapes are shown in Fig. 3 to 8, the shapes are characterized by the two extreme situations when oscillating, one in solid lines, the other in dotted lines. For reasons of clearness the oscillating structure is shown by the single components in most cases.

The characterization of the mode shapes, as can be interpreted with the comparatively small number of measuring points applied, and at the present state of analyzation, is as follows:

The 1st mode (Fig. 3) is a rocking mode with both components in phase, motion strong in the x- and weak in the z-direction. Mode number 2 (Fig. 4) shows both components moving against each other. The 3rd mode (Fig. 5) is supposed to be a bending mode of component 1 with small vertical movement. Mode number 4 (Fig. 6) shows vertical oscillation of both components. Torsional modes as well as bending modes of outer and inner structures follow. An example of a torsional mode is shown in Fig. 7, mode number 9, and one of a bending mode of the inner structure in Fig. 8, mode number 11.

Much more information than can be presented here can be extracted from the measurements available on tape. More measuring points would give more detailed information with respect to the mode shapes.

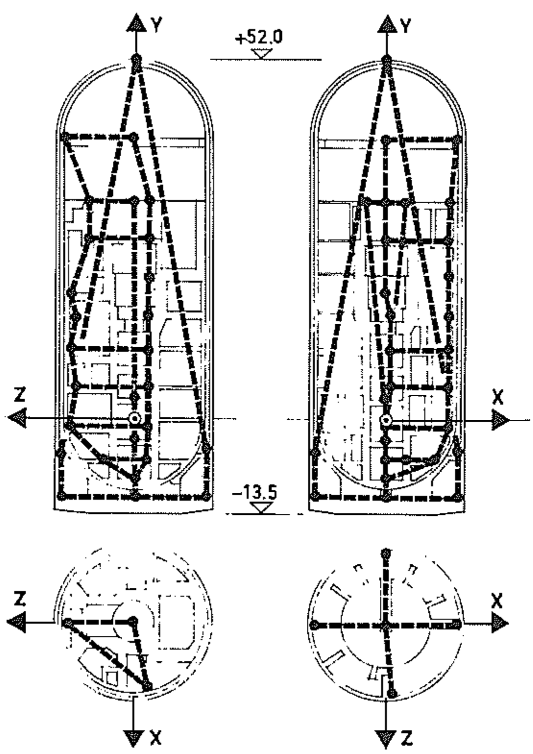

Fig. 1 HDR Nuclear Power Plant with Measuring Points and Grids; Plans and Elevations.

Table of the natural frequencies determined

Mode No.	Frequencies in Hz: Presented Method	Reference [3]	Reference [4]
1	1.45 - 1.56	1.52 - 1.57	1.35 - 1.54
2	2.56 - 2.65	2.63 - 2.81	2.44 - 2.66
3	3.30 - 3.35	3.35	
4	4.56		
5	5.05 - 5.25		4.98 - 5.00
6	5.75 - 5.95		5.70 - 5.90
7	6.35 - 6.70		6.32 - 6.54
8	7.20 - 7.25		7.32
			7.80
	(8.20)	8.16	
	(8.75)		8.50
9	9.75		
10	11.20 - 11.35		11.36 - 11.58
11	12.44	12.25	
12	13.25 - 13.35	12.80	13.00 - 13.22
13	14.00	13.88	14.20
	(14.45)	14.60	
14	15.75	15.25	15.07 - 15.26

In brackets: No distinct results

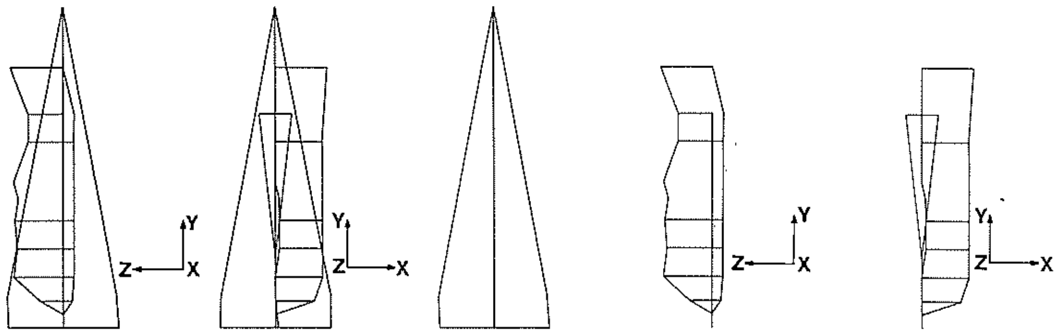

Fig. 2 Grids of the undeformed structure, total views, component 1 and component 2 respectively.

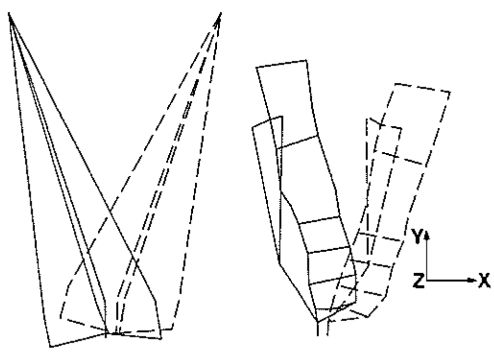

Fig. 3 Mode Shape No. 1
Frequency 1.50 Hz

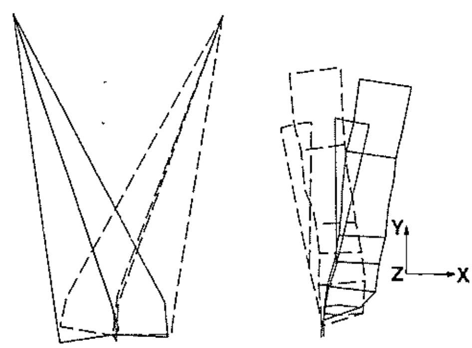

Fig. 4 Mode Shape No. 2
Frequency 2.56 Hz

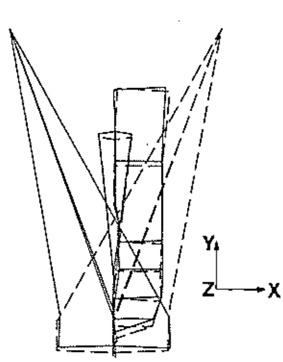

Fig. 5 Mode Shape No. 3
Frequency 3.31 Hz

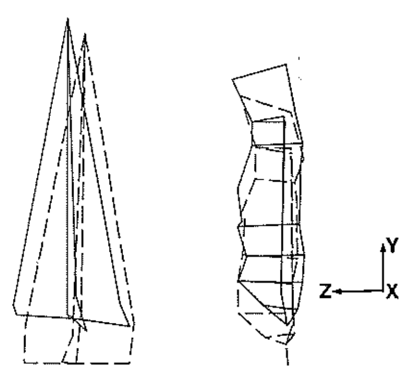

Fig. 6 Mode Shape No. 4
Frequency 4.56 Hz

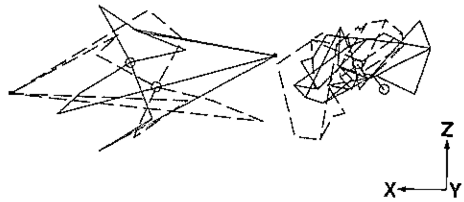

Fig. 7 Mode Shape No. 9
Frequency 9.75 Hz

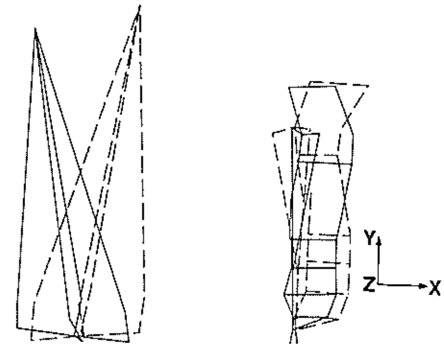

Fig. 8 Mode Shape No. 11
Frequency 12.44 Hz

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