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# EXPERIMENTAL DETECTION OF FLOOR RESPONSE SPECTRA

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## SUMMARY

Floor response spectra are usually gained from artificial free field acceleration inputs acting on structures with different damping values. Only in few cases data from real earthquakes are available. By using microtremor excitation to gain modal parameters of structures a lot of response data are present from different types of buildings. As microtremors are believed to have in principle the same characteristics as real earthquakes - with very low amplitudes - it seems possible to detect amplification ratios for different floors from those measurements. Results are presented from a twelve story highrise building and from a NPP building.

## INTRODUCTION

In order to calculate the earthquake loading of equipment, machinery, pipes, and so on which are fixed to a certain floor of the building at a distinct point, the floor response spectra have to be known. The method of response spectra in order to calculate earthquake loading of buildings has its origin in the work of Housner (Ref. 1). Response spectra depend on the frequencies and damping of the structure considered as well as on the earthquakes occuring at the site of the structure. Calculation of response spectral values requires the evaluation of Duhamel integrals for different types of earthquakes and for different frequency and damping values. This problem is sufficiently solved for practical purposes. But, some problems are left in estimation of floor response spectra, especially in existing buildings for which no or no sufficient calculation of the dynamic behaviour of the structure is available.

If there are maximum amplitudes of different modes of a building during an earthquake, the displacements - or velocities or accelerations - of any location of this building are determined in the considered modes. So these displacements are related to a reference displacement - which might be represented by the displacement at the foundation of the structure - by means of the structure's mechanical behaviour, represented by its mode shapes and its natural frequencies. The stochastical aspect of the problem lies in the unknown mixture of the occuring amplitudes at different earthquake excitations. If e. g. the maximum ground motions at a site are given, the problem can be reduced to the problem of finding the amplification factors by which these maximum ground motion values have to be multiplied to get floor response values.

To get such amplification factors experimentally from available time-history-signals the following considerations can be made: Time-history-response-signals caused by microtremor-, wind-, or traffic-excitation, shortly referred to as "noise excitation" or "ambient vibration" may have a similar characteristic as earthquake excitations; clearly not with respect to the size of the amplitudes and not with respect to the nonstationarity of the stochastic process, but with respect to the stochastic mixture of the amplitudes in the different mode shapes. So it should be possible to compare the maximum values of the time-history-signals at different points of the structure with the corresponding maximum value at a reference point. This comparison leads to the amplification factors mentioned above, if it is made in different frequency ranges.

Extended results of two examples of such measurements compared with a previous paper (Ref. 2) are presented. The time-history-signals used have been recorded in order to gain modal parameters of the considered buildings; for the results of those analysis see example Refs. 3, 4. The 12 story highrise building investigated is the building of the Material Test Institute of Stuttgart University (Fig. 1). The building consists of an eccentric kernel and of slim pillars; its floors had been built on the ground and put into their final position later by the "lift-slab"-method. It measures about 55 m in height and about 24 x 24 m in the ground plan. It represents a comparatively soft structure, which is founded on a stiff rock. The other building considered is the Hot-Steam-Reactor NPP in Kahl/Main, Germany, well known as "HDR"-NPP (Fig. 2). The building measures about 60 m in height and about 20 m in diameter. The plant consists of an outer thin shell structure, shown in black, and an inner structure, which is dotted in the figure (Fig. 2). Inner and outer structure are connected within the foundation plate by a so called "egg cup". In z-direction the outer structure is connected with an additional building. The building is founded on gravel and clay in a river valley, so that the soil-structure-interaction is observable, while the building itsself is rather stiff in its inner structure. It should be mentioned that the building was already slightly damaged by previous heavy experiments when the signals have been recorded.

## METHOD OF ANALYSIS

Sets of synchronous horizontal time-history-signals are available for each of the measuring points, including a reference signal for each set. The time length is about 45 minutes per set. The records have been gained from highly sensitive Willmore type seismometers and consist of vibration velocity signals. The excitation process by "noise" can be considered as stationary and therefore it is different from real earthquake excitation processes. But, if a process is considered which contains all imaginable earthquakes one afther the other, this process might also be stationary and the only difference would consist in the different amplitudes of the two cases. So earthquake response spectra itsself cannot be derived by those measurements, but it might be possible to get the shape of normalized earthquake response spectra (Ref. 2). The probability of occurence of a maximal single modal amplitude with respect to other maximal modal amplitudes during a process of noise excitation is believed to be similar to that one which would occur at any earthquake affecting the considered structure during its lifetime and at its site.

From the time-history-signals the minimum and maximum amplitudes within a frequency bandwidth and within an analyzing time of about 15 minutes, which corresponds to about 1000 cycles in the lowest mode, are found by means of histogramms. The bandwidths investigated were 0-1.56 Hz, 0-2 Hz, 0-3.13 Hz, 0-4 Hz, 0-6.25 Hz and 0-8 Hz in both cases and in addition to these 0-0.78 Hz and 0-1 Hz in the case of the 12 story building. The lowest bandwidth corresponds to the lowest natural frequencies of the structures (Refs. 3, 4). From the mean values of the minima and maxima the amplification factors are calculated for every point with respect to the same reference point. These amplification factors related to a point at the foundation of the 12 story building and to a representative foundation point at the NPP respectively are shown in the tables. In both cases the foundation points are not identical with the reference points, which have been situated in the upper part of the buildings where the largest amplitudes occur.

The bandwidths used were chosen according to the available analyzer, which was a two-channel HP 5423 A instrument. It allows no other distribution of the bandwidths at histograms. As the analyzer has only two channels, each point in each horizontal direction at each bandwidth had to be treated for 15 minutes, a very time-consuming method. So another instrumentation with more channels and arbitrary selectable bandwidths would be able to produce several 15-minute-sets of histograms which could be averaged within the 45 minutes available signal duration and by that means lead to more significant results. Nevertheless, the results gained by only 15 minutes of analyzing time have been shown to be stable and to give reasonable values of the amplification factors.

## RESULTS

The amplification factors gained from vibration velocity signals are shown in table 1 for the 12 story highrise building and in table 2 for the NPP-building. According to the differentiation rules for spectral densities these factors are the same for accelerations and displacements respectively. The results clearly show the dependence of the amplification factors on the mode shapes of the structures, especially in the lowest frequency ranges. At higher bandwidths the influence of the single mode shapes cannot be seen because more mode shapes are present in a stochastical mixture. However, the influence of the soil can be seen clearly.

The 12 story highrise building shows mostly coupled bending-torsion modes. Only mode 5 is a single bending mode in z-direction (Ref. 4). For the first two modes the kernel acts as a center of rotation, which explains the different values in the first column of table 1 also with respect to their descend with lower floor numbers. This behaviour is generally visible in all columns, but less significant at higher bandwidths, caused by the higher mode shapes acting in these ranges. Remarkably low are the values at the foundation point F. It's true that the excitation of this soft building might mainly be caused by wind and not by microtremors, but nevertheless the excited mode shapes are mode shapes of the whole building including its foundation, so that similar results should occur in earthquakes. The amplification values are normalized to the average value of the y-direction of point F.

The HDR-NPP has two dominant mode shapes: A rocking mode (no. 1), where inner and outer structures are rocking in phase on the ground - nearly a rigid body motion. Mode no. 2 shows a counterphase movement of outer and inner structure. Both mode shapes are shown in at least two frequencies due to the rotational symmetry of the building, only disturbed by a coupling to another building. The amplification factors reflect this behaviour in general, where it should be mentioned that point no. 1 is the single point representing the outer structure. It shows considerable lower values in z-direction than in x-direction due to its coupling to the other building. This difference is not as clear with the inner structure which is connected less stiff to the other building that the outer structure. The factors for the foundation points 17 to

21 show a more complicated behaviour. This is due to the supposed damage of the foundation plate during previous tests with a pendulum and shakers. The amplification factors are normalized to the average value of all foundation points in both directions, and the z-direction of point no. 21 served as a reference point. In this building remarkably lower amplification factors occur from foundation to the top than within the 12 story building. This is due to the considerable soil-structure interaction at the HDR-building and to the high stiffness of the structure.

Table 1: Amplification factors of the 12 story highrise building related to point F, y-direction (Fig. 1)

| Floor | Point No | 0-0.78 Hz | 0-1.00 Hz | 0-1.56 Hz | 0-2.00 Hz | 0-3.13 Hz | 0-4.00 Hz | 0-6.25 Hz | 0-8.00 Hz |
|---|---|---|---|---|---|---|---|---|---|
| y-direction: | | | | | | | | | |
| 12 | 12 | ( ) | ( ) | ( ) | ( ) | 8.6 | 7.4 | 8.1 | 8.2 |
| | 11 | ( ) | ( ) | ( ) | ( ) | 8.6 | 8.8 | 10.1 | 10.3 |
| 10 | 10 | 28.7 | 15.2 | 9.6 | 9.3 | 10.0 | 9.6 | 9.7 | 10.1 |
| | 9 | 23.7 | 13.4 | 7.7 | 8.3 | 8.1 | 7.8 | 8.3 | 9.1 |
| 8 | 8 | 20.2 | 10.5 | 6.8 | 8.7 | 8.2 | 9.7 | 9.7 | 9.8 |
| | 7 | 9.8 | 11.9 | 7.2 | 8.3 | 8.4 | 9.7 | 9.5 | 10.2 |
| 6 | 6 | 22.5 | 8.5 | 5.6 | 6.4 | 8.0 | 8.2 | 7.7 | 8.4 |
| | 5 | 13.1 | 8.6 | 4.8 | 5.6 | 7.6 | 8.1 | 7.7 | 8.0 |
| 4 | 4 | 10.7 | 6.8 | 4.8 | 5.7 | 10.2 | 11.4 | 11.4 | 11.3 |
| | 3 | 8.3 | 7.0 | 4.0 | 6.7 | 8.3 | 8.8 | 8.8 | 9.6 |
| 2 | 2 | 6.6 | 4.2 | 2.5 | 2.7 | 4.2 | 4.9 | 5.1 | 5.7 |
| | 1 | 2.7 | 3.1 | 3.1 | 3.6 | 4.0 | 4.8 | 4.8 | 4.8 |
| | F | | average 1.0 | | | | | | |
| z-direction: | | | | | | | | | |
| 12 | 12 | ( ) | ( ) | ( ) | ( ) | 11.4 | 9.6 | 9.5 | 9.7 |
| | 11 | ( ) | ( ) | ( ) | ( ) | 10.6 | 9.0 | 9.7 | 9.3 |
| 10 | 10 | 10.2 | 14.3 | 10.7 | 11.0 | 9.1 | 10.6 | 10.4 | 10.6 |
| | 9 | 22.1 | 14.2 | 10.5 | 10.8 | 10.7 | 10.4 | 9.5 | 10.3 |
| 8 | 8 | 11.1 | 12.0 | 8.7 | 11.0 | 10.3 | 12.2 | 12.2 | 12.4 |
| | 7 | 19.2 | 11.8 | 8.1 | 10.1 | 9.9 | 11.4 | 11.0 | 11.0 |
| 6 | 6 | 9.3 | 8.6 | 5.8 | 7.1 | 8.8 | 11.2 | 11.0 | 11.2 |
| | 5 | 18.1 | 9.7 | 6.3 | 7.6 | 8.6 | 8.9 | 8.6 | 9.0 |
| 4 | 4 | 6.5 | 8.7 | 7.3 | 7.8 | 8.7 | 9.3 | 9.7 | 9.4 |
| | 3 | 12.6 | 8.5 | 5.8 | 7.2 | 9.9 | 10.7 | 11.1 | 11.3 |
| 2 | 2 | 3.7 | 4.4 | 3.3 | 3.6 | 4.1 | 6.5 | 6.2 | 6.7 |
| | 1 | 6.2 | 1.9 | 2.4 | 2.6 | 4.2 | 4.0 | 4.6 | 9.4 |
| | F | | average 0.52 | | | | | | |

Brackets indicate not accurate values, because the signals were disturbed by electric fields in the 12. story.

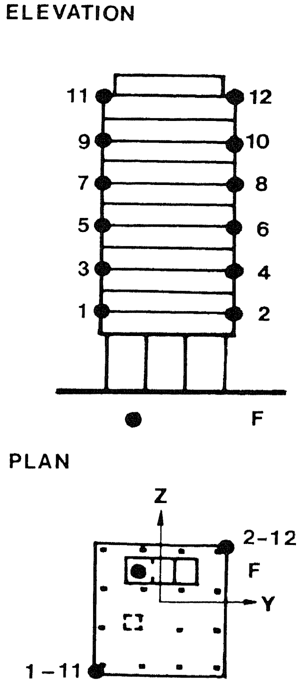

Fig. 1
Building of the Material Test Institute Stuttgart University, with measuring points.

Lowest natural frequencies (measured values):

| Mode No. | | Mode No. | |
|---|---|---|---|
| 1 | 0.73 Hz | 11 | 5.60 Hz |
| 2 | 0.76 Hz | 12 | 6.13 Hz |
| 3 | 1.07 Hz | 13 | 6.54 Hz |
| 4 | 2.39 Hz | 14 | 6.79 Hz |
| 5 | 2.56 Hz | 15 | 7.01 Hz |
| 6 | 3.81 Hz | 16 | 7.10 Hz |
| 7 | 4.00 Hz | 17 | 7.53 Hz |
| 8 | 5.10 Hz | 18 | 7.62 Hz |
| 9 | 5.32 Hz | 19 | 7.82 Hz |
| 10 | 5.51 Hz | | |

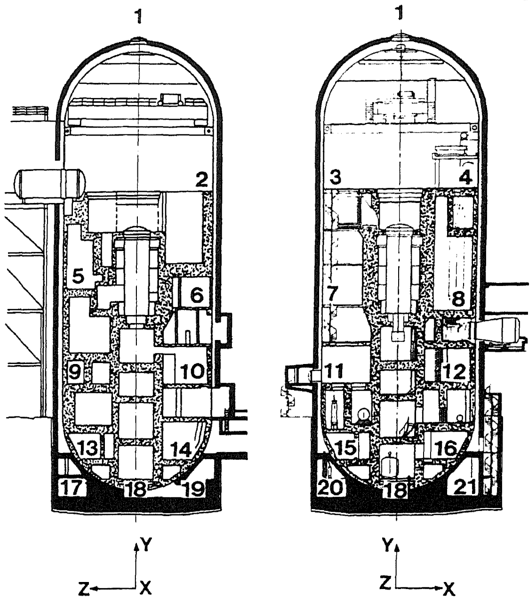

Fig. 2 Elevation of the HDR nuclear power plant with measuring points.

Lowest natural frequencies (measured values):

| | | |
|---|---|---|
| Mode No. | 1A | 1.49 Hz |
| | 1B | 1.53 Hz |
| | 2A | 2.56 Hz |
| | 2B | 2.63 Hz |
| | 3 | 3.35 Hz |
| | 4 | 4.56 Hz |
| | 5 | 5.06 Hz |
| | 6 | 5.17 Hz |
| | 7 | 5.84 Hz |
| | 8 | 6.55 Hz |
| | 9 | 7.19 Hz |
| | 10 | 7.83 Hz |

Table 2: Amplification factors of the HDR nuclear power plant, related to point 21, z-direction (Fig. 2)

| Point No | 0-1.56 Hz | 0-2.00 Hz | 0-3.13 Hz | 0-4.00 Hz | 0-6.25 Hz | 0-8.00 Hz | 0-1.56 Hz | 0-2.00 Hz | 0-3.13 Hz | 0-4.00 Hz | 0-6.25 Hz | 0-8.00 Hz |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| x-direction: | | | | | | | z-direction: | | | | | |
| 1 | 7.20 | 5.19 | 6.48 | 3.93 | 3.08 | 3.31 | 3.90 | 3.25 | 5.80 | 3.51 | 2.86 | 3.24 |
| 2 | 6.57 | 4.74 | 6.40 | 3.95 | 3.01 | 3.20 | 5.78 | 4.84 | 5.80 | 3.65 | 2.90 | 3.01 |
| 3 | 6.41 | 4.57 | 5.88 | 3.65 | 2.90 | 3.01 | 6.65 | 5.09 | 6.14 | 3.74 | 3.16 | 3.20 |
| 4 | 5.19 | 4.84 | 6.87 | 4.26 | 3.36 | 3.49 | 5.24 | 4.03 | 5.23 | 3.25 | 3.06 | 3.35 |
| 5 | 4.66 | 3.14 | 4.05 | 2.23 | 1.77 | 2.71 | 4.17 | 2.64 | 3.41 | 2.31 | 2.10 | 2.41 |
| 6 | 3.97 | 2.37 | 3.53 | 2.06 | 1.63 | 1.78 | 3.74 | 2.04 | 3.09 | 1.92 | 1.53 | 2.01 |
| 7 | 4.37 | 2.69 | 3.46 | 2.23 | 1.77 | 1.92 | 4.18 | 3.14 | 3.68 | 2.87 | 2.79 | 2.73 |
| 8 | 3.28 | 2.03 | 2.63 | 1.83 | 1.34 | 1.70 | 4.56 | 2.92 | 4.14 | 2.50 | 2.10 | 2.14 |
| 9 | 2.99 | 2.08 | 2.27 | 1.46 | 1.16 | 1.41 | 4.41 | 2.79 | 3.17 | 1.83 | 1.66 | 1.72 |
| 10 | 1.83 | 1.18 | 1.19 | 0.77 | 0.61 | 0.66 | 2.34 | 2.23 | 2.18 | 1.22 | 0.97 | 1.02 |
| 11 | 2.99 | 2.08 | 2.10 | 1.30 | 1.04 | 1.08 | 3.47 | 2.28 | 2.45 | 1.46 | 1.23 | 1.27 |
| 12 | 2.14 | 2.14 | 2.18 | 1.35 | 1.00 | 1.02 | 3.89 | 2.66 | 1.68 | 1.10 | 0.88 | 0.93 |
| 13 | 1.78 | 1.76 | 1.96 | 1.22 | 1.22 | 1.27 | 1.92 | 1.76 | 2.27 | 1.22 | 0.85 | 0.79 |
| 14 | 1.19 | 1.04 | 1.65 | 1.50 | 1.19 | 1.28 | 0.95 | 0.88 | 2.27 | 1.02 | 0.81 | 0.95 |
| 15 | 1.60 | 1.14 | 1.73 | 1.42 | 1.13 | 1.34 | 1.05 | 0.82 | 1.73 | 1.29 | 1.37 | 1.27 |
| 16 | 2.75 | 1.14 | 1.47 | 1.22 | 0.97 | 0.93 | 0.97 | 0.76 | 0.89 | 0.76 | 0.73 | 0.78 |
| 17 | 0.58 | 0.59 | 0.67 | 0.43 | 0.40 | 0.49 | 0.74 | 0.75 | 1.14 | 0.68 | 0.55 | 1.33 |
| 18 | 1.75 | 0.98 | 1.96 | 1.22 | 0.97 | 1.41 | 1.01 | 0.98 | 2.27 | 1.46 | 1.35 | 1.41 |
| 19 | 1.75 | 0.98 | 1.57 | 1.22 | 1.35 | 1.41 | 1.75 | 1.06 | 1.36 | 0.97 | 0.97 | 0.94 |
| 20 | 0.56 | 0.47 | 0.78 | 0.53 | 0.39 | 0.40 | 0.69 | 0.60 | 1.07 | 0.65 | 0.59 | 0.60 |
| 21 | 0.52 | 0.58 | 0.83 | 0.54 | 0.48 | 0.52 | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 | 0.63 |

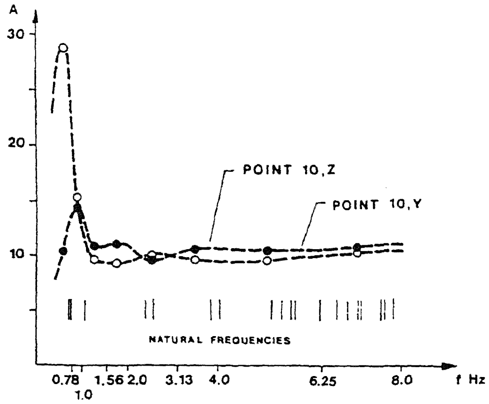

Fig. 3 Amplification factors for the 12 story building

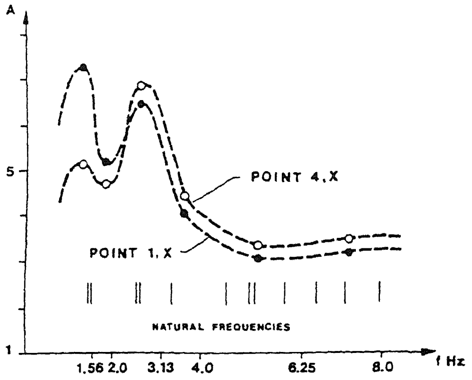

Fig. 4 Amplification factors for the HDR-NPP

Fig. 3 and Fig. 4 show the amplification factors for selected points of the considered buildings.

## CONCLUDING REMARKS

The results show that the amplification factors depend considerably on the vibration behaviour of the building. Although the results were gained from comparatively short time-history-signals it is believed that longer analyzing times or different noise levels of the excitation process will not change the results significantly. The method presented seems to be useful to gain such amplification factors by noise excitation measurements in any kind of buildings. The method might become important in detecting floor response values in existing buildings, to avoid expensive calculations.

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