MEASUREMENTS OF THE VIBRATIONS OF A BUILDING

MESSUNGEN DER SCHWINGUNGEN EINES GEBÄUDES

MESURAGE DES OSCILLATIONS D'UN BÂTIMENT

Anne Jüngert, Christian U. Grosse

SUMMARY

A building is set into vibrations by wind, traffic and machines. Although the incitation covers a broad frequency range, the building will adopt the vibrations most, which correspond to the natural periods of the building. If the incitation gets very strong in the range of the natural frequencies e.g. due to an earthquake, the building can experience strong damage.

Using a seismometer the ambient ground motion was recorded in the basement and on the roof of a four-storey-building in Pfaffenwaldring 2 B in Stuttgart for 40 hours. By consideration of the power spectral densities the data analysis was done in the frequency domain. Different measurements are compared and checked for relevant frequencies. Finally the spectra are compared to theoretical determined natural frequencies, estimated using formulas known from engineering seismology.

ZUSAMMENFASSUNG

Durch Wind, Verkehr und Maschinengeräusche wird ein Bauwerk zu Schwingungen angeregt. Obwohl die Anregung ein breites Frequenzspektrum abdeckt, nimmt das Bauwerk die Schwingungen am stärksten auf, die den Eigenfrequenzen des Bauwerks entsprechen. Bei zu starker Anregung im Bereich der Eigenfrequenzen, z.B. durch ein Erdbeben, kann es zu starken Schäden am Gebäude kommen.

Mithilfe eines Seismometers wurde das Umgebungsrauschen im Gebäude Pfaffenwaldring 2 B in Stuttgart im Keller und auf dem Dach über einen Zeitraum von 40 Stunden aufgezeichnet. Über die Darstellung der Leistungsdichtefunktion findet eine Auswertung im Frequenzbereich statt. Die unterschiedlichen Messungen werden miteinander verglichen und auf relevante Frequenzen untersucht. Schließlich werden die Spektren mit Formeln aus der Ingenieurseismologie hinsichtlich der theoretischen Eigenfrequenzen untersucht.

RESUME

Par l'action du vent, de la circulation et du bruit provenant de machines, un bâtiment est généralement excité à effectuer des oscillations. Bien que l'excitation couvre une bande fréquentielle assez large, le bâtiment montre la réaction la plus prononcée aux oscillations qui correspondent à ses fréquences propres. Lors d'une excitation excessive dans les environs de ces fréquences, par exemple suivant un tremblement de terre, des dommages considérables peuvent résulter.

Avec un sismomètre le bruit sismique a été enregistré dans la cave et sur le toit du bâtiment Pfaffenwaldring 2 B à Stuttgart durant 40 heures. Utilisant la représentation graphique de la fonction densité puissance, une évaluation est effectuée dans de domaine fréquentiel. Les différents enregistrements sont comparés et analysés pour detecter les fréquences relevantes. Finalement les spectres sont étudiés pour retrouver des fréquences propres théoriques calculées à l'aide de formules provenant de la sismologie.

KEYWORDS: Building Vibrations, Natural Periods, Seismic Noise

1 INTRODUCTION

In the past it turned out that buildings can experience strong damage when they get excited with their natural frequencies. Such phenomena were observed e.g. in the earthquake that destroyed many buildings in Mexico City in 1985. The seismic waves resonated in the soft sediment and the frequencies happened to match with the natural frequencies of tall buildings. These buildings were severely damaged although the earthquake’s epicentre was 350 km away from Mexico City. Also at risk are bridges which start to oscillate due to wind excitation. The most famous example is the Tacoma-Narrows-Bridge which was totally destroyed.

Thus the knowledge of the natural frequencies of a building can sometimes be important but is hard to calculate. Many factors must been taken into account and often a numerical modelling is necessary. If an existing building is set into vibrations through wind excitation, it can be assumed that the oscillation will be a superposition of the fundamental modes of the system of building underground. To find out about the natural frequencies of a building we can use ambient ground motion, in the following simply called noise ([2]). The noise is recorded continuously for several hours and then analysed in the frequency domain.

2 EQUIPMENT AND THEORY

It is not easy to calculate the natural vibrations of a building without a good knowledge of the structure. The natural frequencies depend e.g. on the stiffness of the building which is related to many factors as geometry, building materials and ground plan. There are several formulas to calculate the lowest natural frequency roughly. In engineering seismology ([3]) they often use a relationship between the amount of storeys *N* and the natural period *T* which is given by

$$T = \frac{N}{10}[s] \tag{1}$$

This estimation is very rough but is often adequate to predict hazards due to an earthquake. An estimation of the Uniform Building Code ([7]) takes into account, that buildings are made nowadays out of reinforced concrete and therefore have different stiffness. The equation 2 uses the height *h* in feet of a building to determine its natural period.

$$T = 0.03h^{\frac{3}{4}}[s] \tag{2}$$

An empirical formula is given by equation 3 ([4]). It takes the short and long edge of a rectangular building into account.

$$T = \frac{0.05h}{\sqrt{d}}[s] \tag{3}$$

where *h* is the height in feet and *d* the dimension of the building parallel to the applied forces in feet. Usually this estimation is used for wind-induced vibrations.

To measure the vibrations of the building Pfaffenwaldring 2 B in Stuttgart a seismometer was placed at different locations in the building. Measurements took place in the basement and on the roof of the building Pfaffenwaldring 2B. The sensor was a 3-component seismometer from Lennartz Electronics with a natural period of 1 s. The recording of the data was using the MARSLite-equipment of the same company including a magneto-optical drive. The equipment is shown in Figure 1. The amplitude transfer function of the seismometer is shown in Figure 2. The frequency response above 1 Hz is constant. Below 1 Hz the response decreases exponentially.

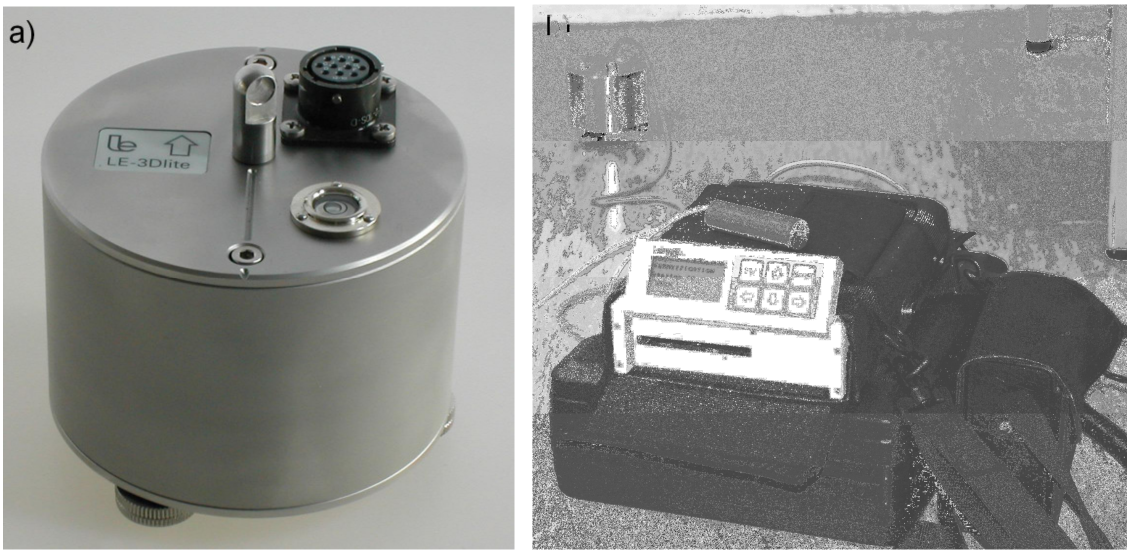

Figure 1: a) Seismometer LE-3DLite, b) MARSLite equipment with seismometer

To measure building vibrations data were continuously registered. The measurement started usually on an afternoon followed by a holiday or a Saturday and ran for 40 hours until the disc was full.

The data analysis was done using the program PITSA (Programmable Interactive Toolbox for Seismological Analysis, [6]). The recorded raw data were filtered with a Butterworth highpass filter using a cutt-off frequency of 0.01 Hz. Regarding the amplitude transfer function (Figure 2) of the sensor it can be assumed that lower frequencies can't be registered well by the seismometer. After that the first 3 minutes of data acquisition were cut out, because there are a lot of high amplitudes due to the staff walking around the room and placing the equipment right.

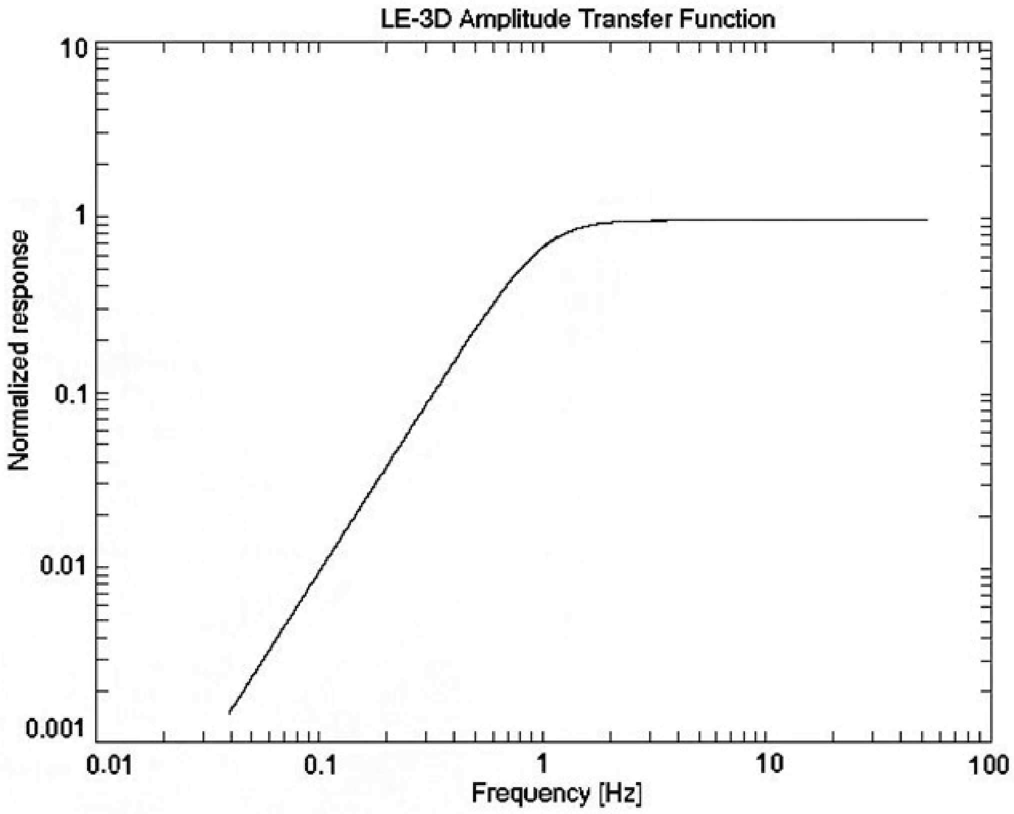

Figure 2: Amplitude Transfer Function of the seismometer

Then the horizontal components had to be rotated because the orientation of the seismometer was 45° to the edges of the building. PITSA provides a function to rotate the horizontal components to any direction. The N-component was rotated to the long edge, the E-component to the short edge of the building. The advantage can be seen in Figure 3, which shows the horizontal particle motion of a reference event. The biggest amplitude is related to an angle 105° to north. This matches well to the direction of the source of the event.

After the rotation the power spectral density of the signals was determined using the built-in function of PITSA.

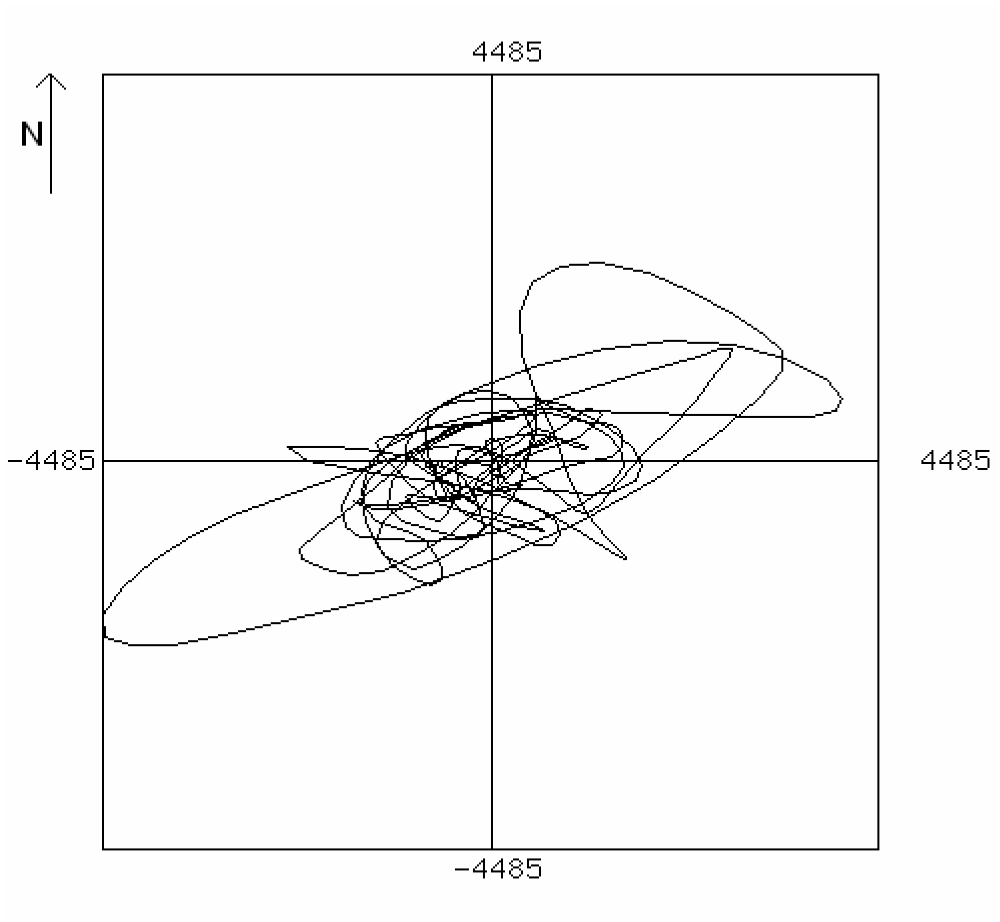

Figure 3: Horizontal particle motion of a reference event

3 RESULTS

3.1 First measurements

At first some measurements were used to determine basic characteristics of the ambient noise. The seismometer was set on the ground of the basement to record the noise. The measurement was disturbed from time to time by people entering the room through the door. The opening and closings of the door can be used as control event. The measurement started on May 30th at 11:37 UTC (Universal Time Coordinated). The door was opened and closed at 14:35 UTC on May 30th, at 7:15 UTC and at 13:39 UTC on May 31st. Regarding the vertical component of the time series in Figure 4 the door-closings can be detected very well. They are the biggest events recorded. Different noise levels during day and night can be observed using Figure 4.

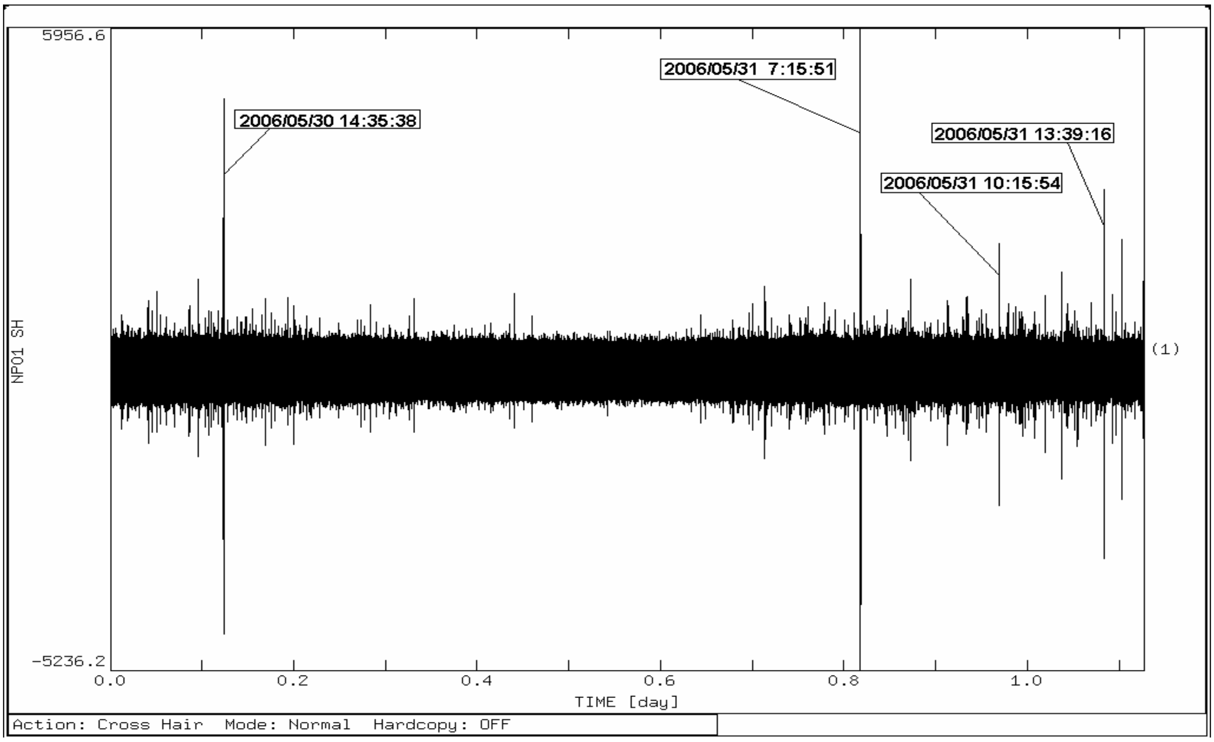

Figure 4: Time series of the vertical component

3.2 Measurements in the basement

The next measurement was located in the optical laboratory in the basement of Pfaffenwaldring 2 B. The measurement started on June 15th which was a holiday. Nobody entered the laboratory while the seismometer was recording. The ground motion due to wind, traffic and people walking around the building was recorded. Usually power spectral density function turns out to be a good way to observe the vibrations of buildings ([1], [5]). This is the reason why according algorithms were applied to the data first.

In Figure 5 the power spectral density is shown for ground motion measurements in the basement. All three components are scaled in the same way. The frequency range was limited to 80 Hz because only little energy is transmitted above 60 Hz. The maximum amplitude on the vertical component (Z-component) is about two times larger than on the horizontal components. In Figure 6 the y-axis is cut-off at 2000 W/Hz to display the smaller peaks better.

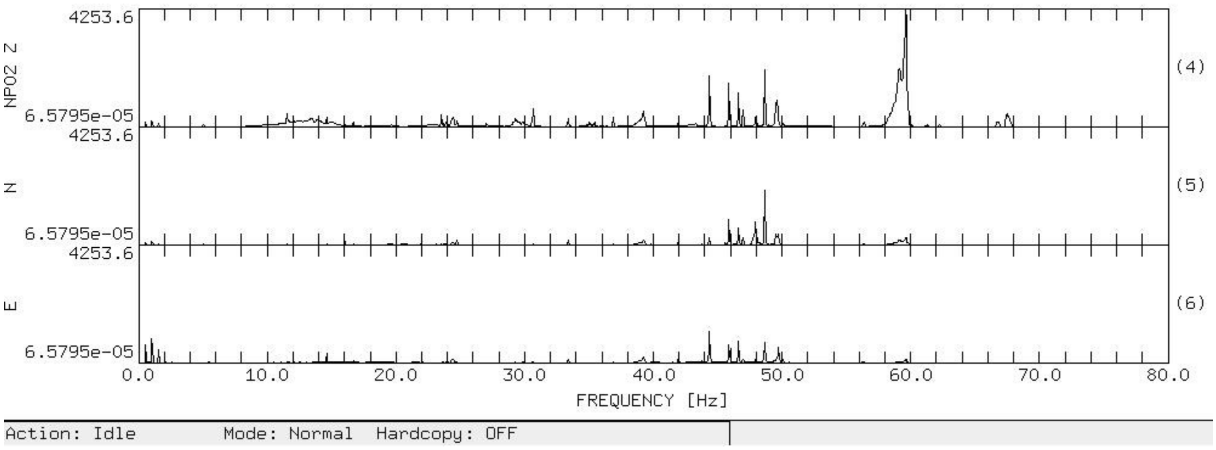

Figure 5: Power spectral densities of the measurement in the basement

Some frequencies are visible on all components but the amplitudes differ. On the vertical component there's greater variety in frequencies. The biggest peak on the vertical component is at 60 Hz. Several peaks can be found between 44 Hz and 50 Hz, at about 39 Hz, 37 Hz, 35 Hz, 33.5 Hz, 31 Hz, 29 Hz and 24.5 Hz. Almost all frequencies between 8 Hz and 18 Hz were excited.

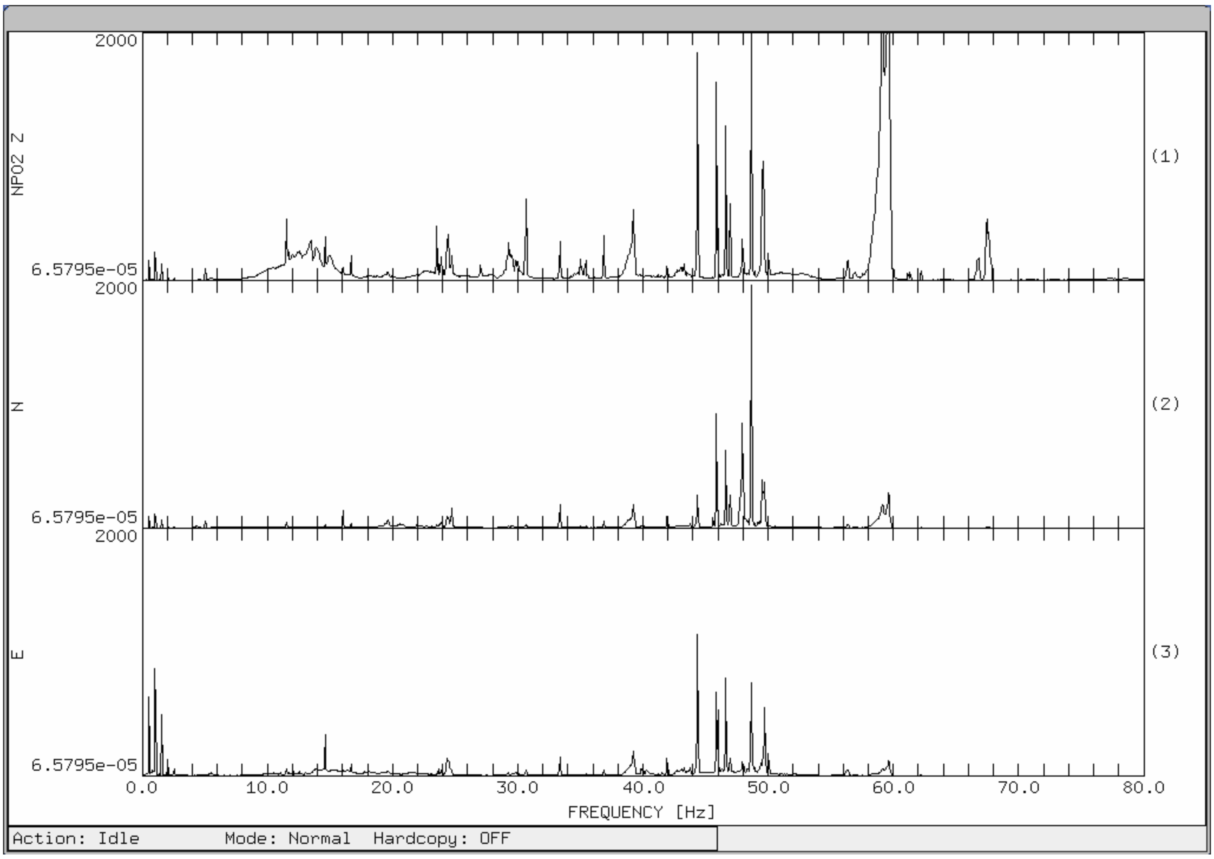

Figure 6: Power spectral densities of the measurement in the basement

On the horizontal components there is also energy transmitted at 60 Hz and at several peaks between 44 Hz and 50 Hz. Likewise nearly all peaks seen on the vertical component can be found on the horizontal components as well.

3.3 Measurements on the roof

On July 28th the equipment was placed on the roof of the building Pfaffenwaldring 2 B. It is expected that the vibrations will be much larger than in the basement. Figure 7 shows the power spectral densities of the three components all scaled to the maximum of the vertical component.

The most energy in vertical direction is transmitted between 50 Hz and 70 Hz. The maximum peak can be seen at 50 Hz. Located on the roof of the building is the control of the air conditioning system. These machines can cause additional vibrations which can't be measured in the basement.

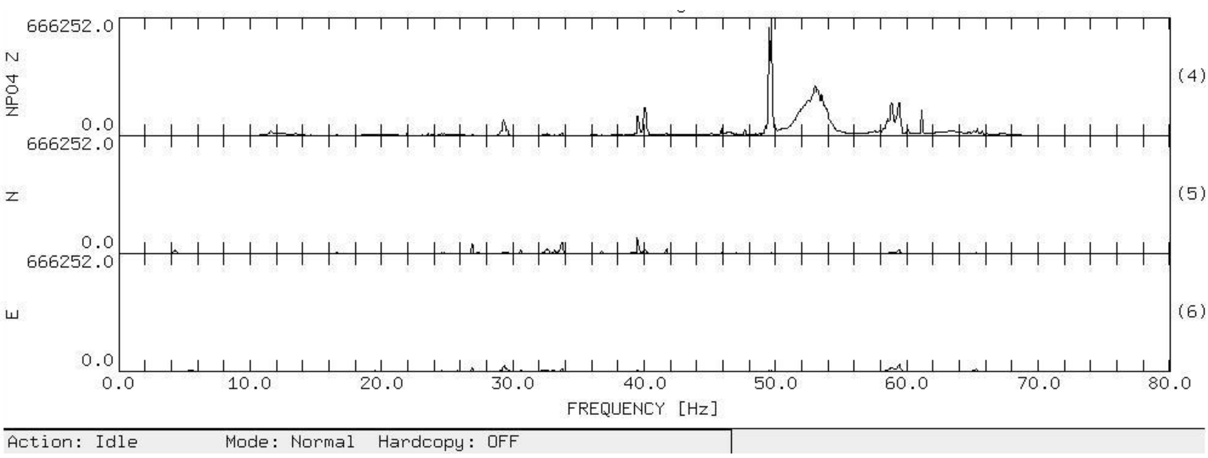

Figure 7: Power spectral densities of the measurement on the roof

Figure 8 shows the power spectral densities of this measurement. The y-axis is cut at 90000 W/Hz.

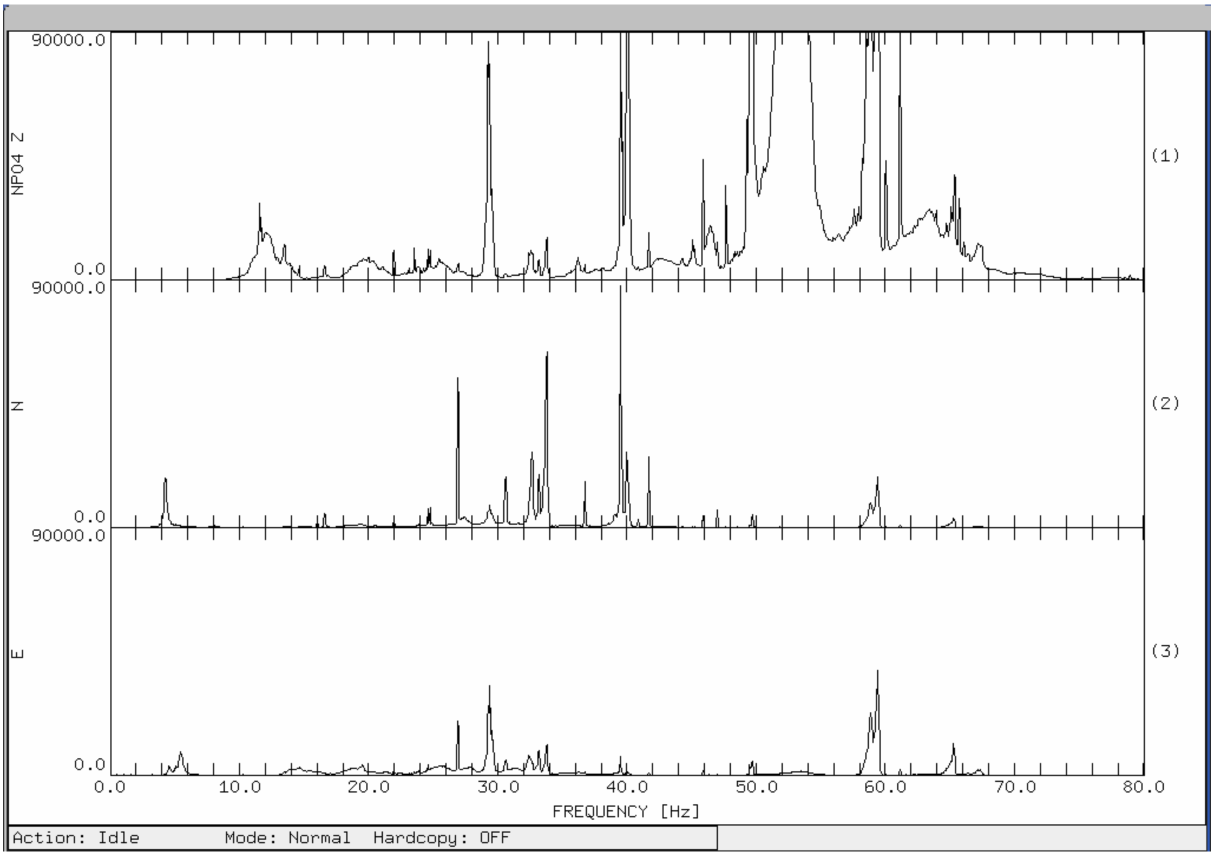

Figure 8: Power spectral densities of the measurement on the roof

On the vertical component you can see a kind of continuous spectrum between 50 and 60 Hz. The highest peak is located at 50 Hz. On the horizontal component directed parallel to the long edge of the building the highest energy is observed at about 40 Hz. In direction of the short edge energies are much smaller and the highest peak is located at about 30 Hz.

Again we can see several frequencies on all three components, e.g. 60 Hz, 39 Hz, 50 Hz and 29 Hz. On the horizontal components additionally energy is visible at about 4 Hz.

3.4 Comparison of the two measurements

In the following pictures one can compare the normalized power spectral density functions of the two measurements. The same components of the different measurements are displayed together in one plot (Figure 9, Figure 10 and Figure 11). Because the energies are much higher on the roof than in the basement, the power spectral densities are displayed normalized, here, to perform a better comparison of the two measurements. The measurements on the roof are coloured in black, the measurements in the basement are coloured in grey.

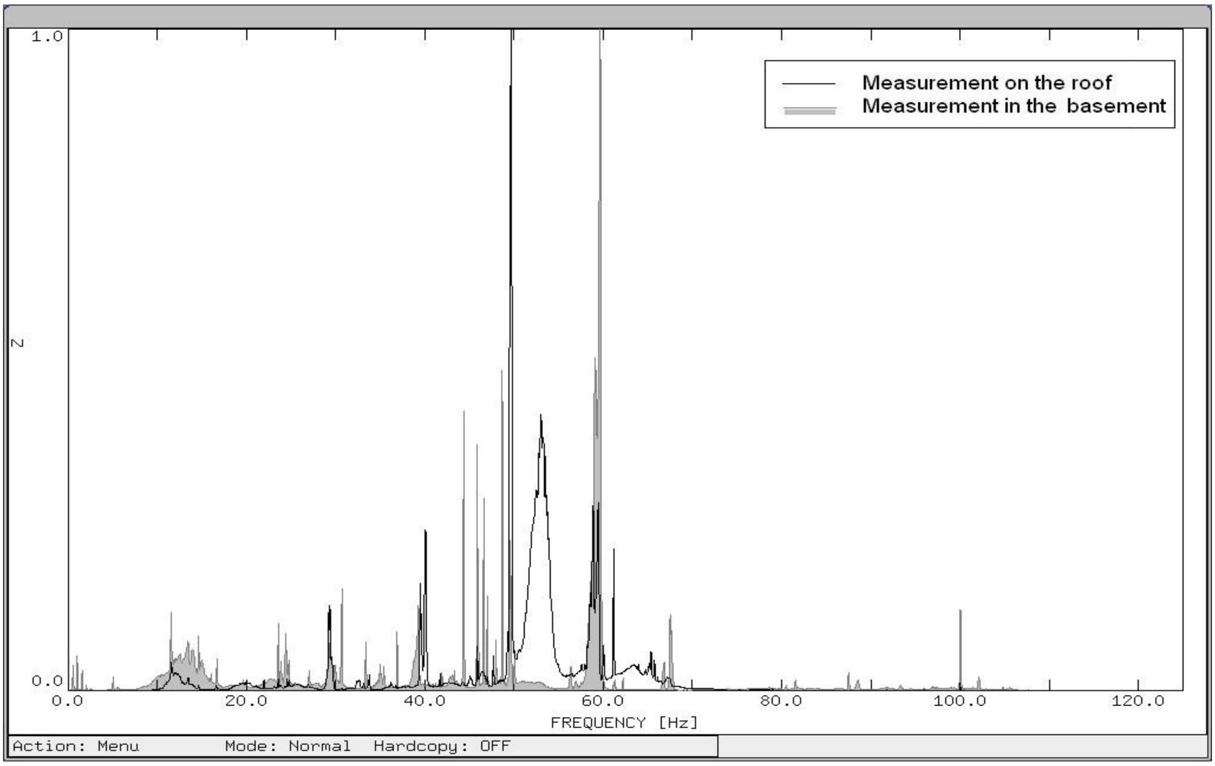

Figure 9: Normalized power spectral densities of the vertical component of both measurements

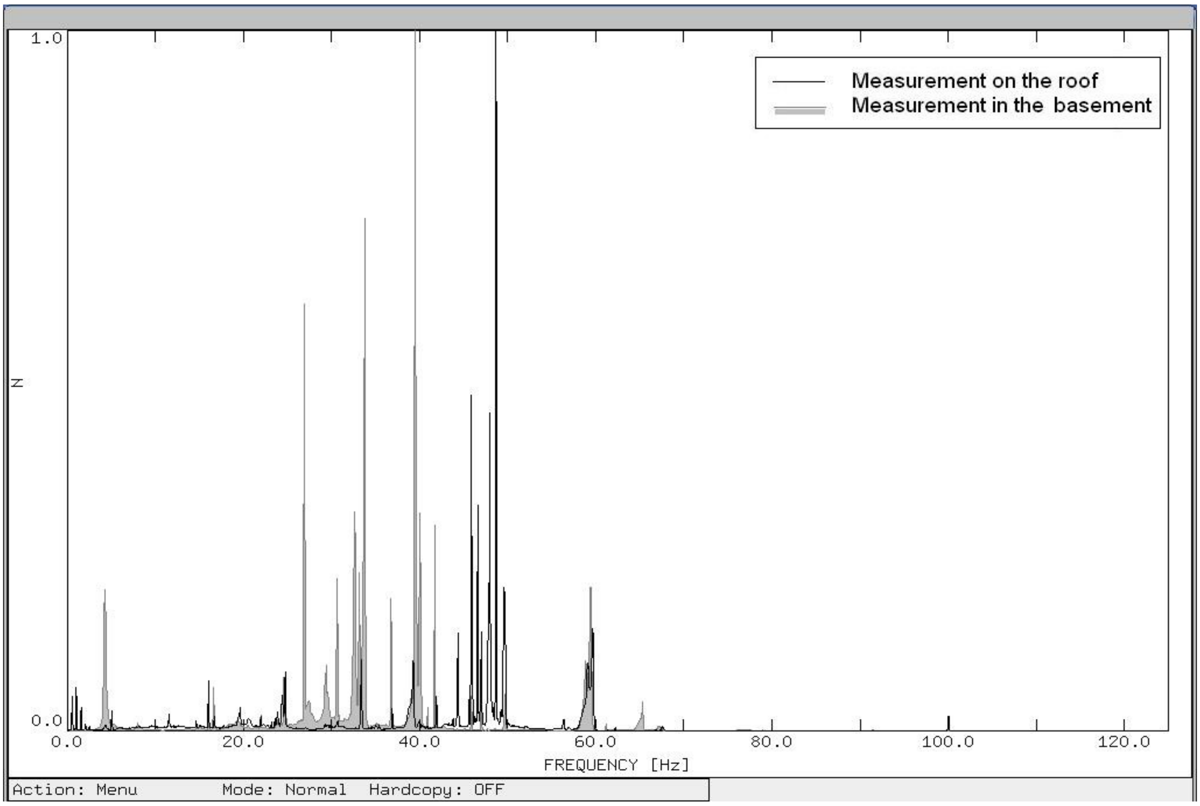

Figure 10: Normalized power spectral densities of the component parallel to the building's long edge of both measurements

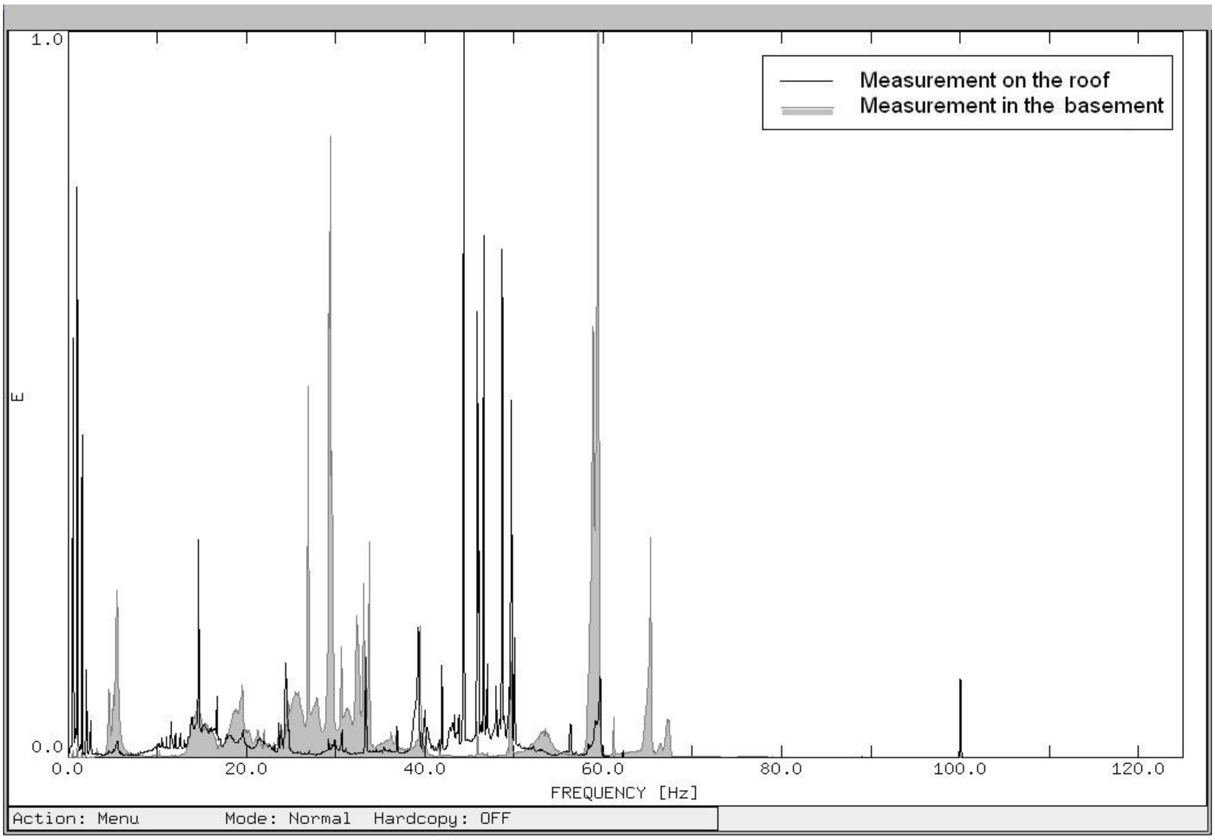

Figure 11: Normalized power spectral densities of the component parallel to the building's short edge of both measurements

The true power spectral densities on the roof are about 45 times higher than in the basement.

Many frequency peaks of both measurements correspond, e.g. at 60 Hz, 41 Hz and 29 Hz. These frequencies are related to the building or the underground. In the basement higher frequencies about 40 Hz to 50 Hz are transporting more energy than on the roof. On the roof more energy is transmitted by lower frequencies about 25 Hz to 40 Hz. On the vertical component there's a high energy transport between 50 Hz and 60 Hz in the measurement on the roof. As this is not seen in the basement it stands to reason that this is caused by the air conditioning system which has its control on the roof.

If we calculate the natural frequencies by the equations given in Chapter 2 and the dimensions of the building, we get the following frequencies. Equation 1 gives for the 4-storey-building (including basement) a natural frequency of 2.5 Hz. Equation 2 and a height *h* of about 18 metres (59 ft) the natural frequency 1.5 Hz can be calculated. Equation 3 distinguished between the edges of a rectangular building and leads to a frequency of about 3 Hz for the short (23 m) and about 4 Hz for the long (42 m) edge of the building. We can find a peak at 4 Hz in the horizontal components. There's also a peak at 1.5 Hz and 2 Hz. Most of the energy is, however, observed at higher frequencies.

4 DISCUSSION AND CONCLUSION

Power spectral density functions were calculated using the time series recorded in the building Pfaffenwaldring 2B. The ground motion recorded during ambient conditions is able to make observations in a broad frequency range. In the spectra of the measurements there are clear peaks at many frequencies which mirror the natural frequencies of the building-underground system. The same frequencies are found using recordings of a sensor on the roof and in the basement as well. We can assume, that these frequencies contain the natural periods of the system of building and underground. The comparison of the measurement in the basement and on the roof shows a good congruence in many frequencies, although the measurement on the roof shows generally higher amplitudes at lower frequencies.

The more exact analytical determination of natural frequencies of a building is very difficult as the construction material used and the details of the structure including reinforcement must be known very well. A couple of rough formulas were found empirically. Regarding the building Pfaffenwaldring 2 B natural frequencies were calculated based on rough theoretical models. These frequencies can be found in the power spectral density functions but one has to consider that the shape of the building is very complex, what leads to many uncertainties. A significant part of the vibration energy, however, is observed at higher frequencies. The equations used here, are from the engineering seismology and should roughly predict which frequencies caused by an earthquake could affect a building. Indeed an earthquake exceeds a broad spectrum, but the high frequencies are damped very fast and the engineering seismologists only take into account the frequencies up to 10 Hz. A building obviously has natural frequencies also in a higher frequency range. These are not covered in the estimations. As the building is linked to the underground they are acting as a system which of course has other natural periods than the building alone. Furthermore the used estimations are developed using data of typical buildings in California which won't necessarily match to typical German buildings. Besides the building Pfaffenwaldring broke into two parts due to groundwater subsidence. This also changes the natural periods and explains why the calculated frequencies do not match with the measured ones perfectly.

In the spectrum of the measurement on the roof vibrations with high energies are observed between 50 Hz and 60 Hz. The seismometer was placed next to a small construction on the roof containing the air conditioning system to protect it at least a little from the sun as the correct working of the sensor only is warranted up to 35 °C. It can be assumed that the air conditioning caused additional noise.

The observation of building vibrations using ambient noise is possible. We could see that many frequencies are transmitted through the building and the underground. The knowledge of these frequencies is important for seismic hazard assessment. If it would be possible to monitor the natural periods of the building-underground system and detect damages of the building in changes of the natural frequencies, this would be a great opportunity for higher stressed buildings like bridges. To monitor a building it would be an advantage to use very small equipment like MEMS-based (Micro-Electro-Mechanical Systems) accelerometers. As there's not much experience with the MEMS-based recordings, the investigations done here with the conventional equipment will be used as reference measurements.

ACKNOWLEDGEMENT

The authors thank Gerhard Bahr for the technical support during the measurements.

REFERENCES

[1] Crawford, R., Ward, H.S. Determination of the Natural Period of Buildings. BSSA 54 (1964), No. 6, pp. 1743-1756.

[2] Brune, J.M., Oliver, J. The Seismic Noise of the Earth's Surface. BSSA 49 (1959), No. 4, pp. 349-353.

[3] Bozorgina, Y., Bertero, V. Earthquake Engineering – From Engineering Seismology to Performance-Based Engineering. CRC Press, 2004, ISBN 0-8493-1439-9.

[4] Hudson, D.E., Keightley, W.O., Nielsen, N.N. A New Method for Measurement of the Natural Periods of Buildings. BSSA 54 (1964), No. 1, pp. 233-241.

[5] Fäcke, A., Parolai, S., Richwalski S.N., Stempniewski, L. Assesing the Vibrational Frequencies of the Cathedral of Cologne (Germany) by Means of Ambient Seismic Noise Analysis. Natural Hazards 38 (2006), pp. 229-236

[6] Scherbaum, F., Johnson, J., Rietbrock, A. PITSA Users Manual, Version 5.0, 1999, www.geo.uni-potsdam.de/forschung/Software/pitsa.html

[7] Uniform Building Code. Structural Engineering Design Provisions, International Conference in Building Officials, 1997, Whittier, CA.