Office floor vibrations: modal parameter identification and vibration monitoring

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Abstract

Several people working on the 2nd floor of an office building complained about disturbing floor vibrations. The building consists of five floors. In the contrary to the other floors, the 2nd floor slab has no floor-to-ceiling secondary walls neither beneath nor on top of the slab. The modal parameters of four floors were identified using ambient vibration testing (AVT)-technology and a 5-kg-medical ball as a vibration generator. To monitor the vibration intensity and to identify the source of the disturbing vibrations, a triaxial velocity sensor was subsequently mounted in a critical point of the 2nd floor slab. The vibrations were monitored for two months using a newly developed internet-accelerograph. This allowed online checking of the vibrations and downloading of the data on an external server on a daily basis. Processing of these data yielded that no other source of the vibrations could be identified than people walking on the floor.

1 The problem and the approach to find a solution

Several people working on the 2nd floor of an office building complained about disturbing floor vibrations. The building consists of four similar floors. To identify the problem and to achieve a reasonable basis to evaluate a solution, two kinds of tests were performed:

a) System identification of the floors (determination of natural frequencies, mode shapes and damping coefficients),

b) Monitoring of the 2nd floor vibrations for two months.

2 The building

The building consists of five floors. In this paper, the expression "floor" also means the slab carrying the respective floor. Unfortunately, no engineer's drawings showing the slab and the supporting walls from a looking upwards perspective were available. The drawings shown here are the architect's drawings looking down on the respective floor.

The ground floor (slab) being supported by several concrete and masonry walls was not subject of the investigation discussed here. Floors No. 1 to 4 are (most probably) identical concrete slabs sitting on some core walls and some columns arranged at the outer edge of the slabs.

In the contrary to the other floors, the 2nd floor has no floor-to-ceiling secondary walls neither beneath nor on top of the slab (Fig. 1). The other three floors have some floor-to-ceiling secondary walls either beneath (1st and 4th floor) or on top of the slab (3rd floor) (Figs. 2 and 3). Theoretically, these secondary walls are not load-carrying.

The maximum span of the concrete slabs is about 7 m. The slab thickness is unknown.

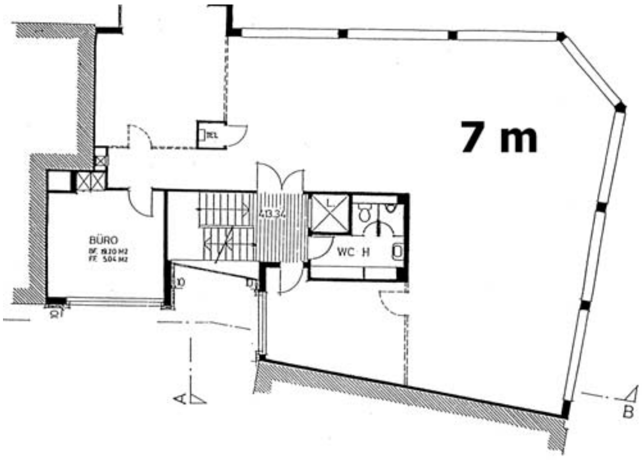

Figure 1: Plan view of the 1st and 2nd floors (cut above the slab and looking down on the slab).

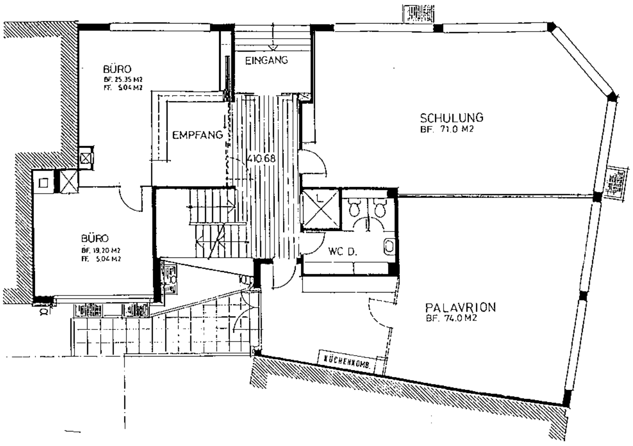

Figure 2: Plan view of the ground floor. The intermediate wall "supporting" the 1st floor slab is probably from masonry.

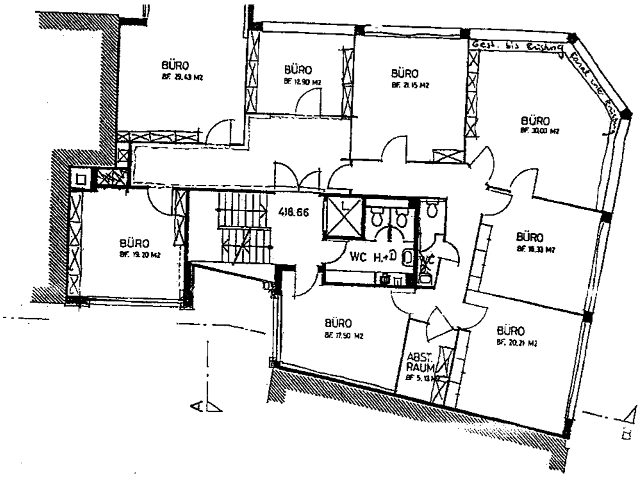

Figure 3: Plan view of the 3rd floor; the 4th floor looks similar. The intermediate walls are probably from gypsum or masonry.

3 Modal parameter identification

3.1 "Ambient excitation"

To determine the structures' modal parameters, a modified Ambient Vibration Technique (AVT) was used. In the contrary to large civil engineering structures where the usual ambient sources of excitation like wind, traffic or seismic micro-tremors are inducing nice structural vibrations, problems may arise when investigating relatively small floors.

To identify the dynamic parameters of such a structure, experience has shown that it is a good idea to artificially increase the level of structural vibrations during the "AVT" investigation. Moving on the floor and dropping a 5 kg medical ball from a height of roughly 1 m at irregular time intervals of one to four seconds has proven to be a very efficient means of excitation for concrete floors exhibiting dimensions of several meters (Fig. 4).

Figure 4: The medical ball used to excite the slabs and one of the accelerometers used to measure the slab response.

The advantages of this procedure are three-fold: a) the vibration level induced in this way is definitely larger than any "noise" vibration induced by any "dynamic" piece of equipment in the building (including the vibrations induced by the ball thrower's walking), b) the impulses generated by the ball (obviously; according to experience) have an optimum duration and the frequency band of interest is excited very nicely, and, c) the risk of the excitation sitting in a node of a structural natural vibration is zero. The latter is a very important advantage versus any kind of Forced Vibration Testing (FVT), where the point of excitation usually has to be kept constant due to practical reasons.

3.2 Response measurements

Piezo-electric sensors PCB 393B31 with a sensitivity of 10 V/g were used to measure the floor vibrations (Fig. 4). The measurement point grid consisted of three vertical reference points and 35 roving vertical measurement points (Fig. 5). The latter were covered with five roving sensors in seven setups.

The sampling rate was s = 100 Hz and the length of the time windows 5 minutes.

During one weekend, the floors No. 1 to 3 were tested in this way in the absence of anybody in the building except the test crew. The 4th floor was tested in a minimum way only. Here, the first couple of natural frequencies were established without determining mode shapes and damping coefficients.

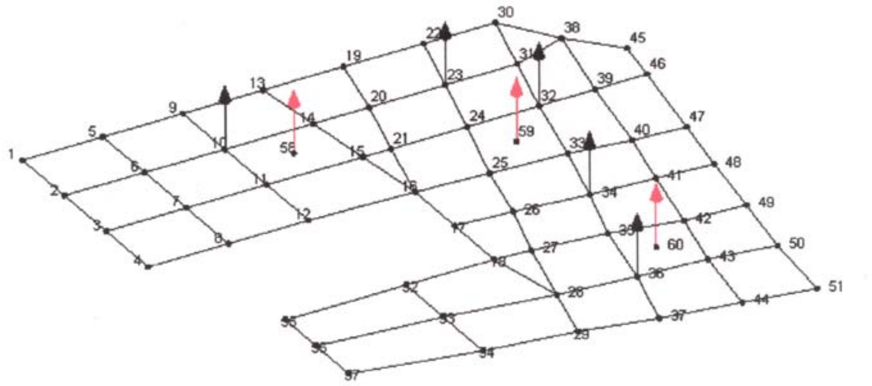

Figure 5: The measurement point grid. The red arrows indicate the position of the three reference sensors (located outside the grid lines), the black arrows the five roving sensors of setup 1. To cover the 35 Measurement points, a total of 7 setups was required.

3.3 Signal processing and results

EFDD (Enhanced Frequency Domain Decomposition) and SSI (Stochastic Subspace Identification) methods as offered from the ARTeMIS Extractor software package were used to identify the modal parameters. Although being based on completely different algorithms, both methods yielded almost identical results (Tables 1 to 3). The largest differences were found for the damping values. However, most of these differences are quite small when compared with the results of tests on other structures.

Mode	f EFDD [Hz]	ζ EFDD [%]	f SSI [Hz]	ζ SSI [%]	MAC EFDD-SSI
1	11.57	2.03	11.52	3.61	0.9938
2	12.84	2.50	12.88	3.12	0.9945
3	17.05	4.91	17.10	5.34	0.9985
4	25.16	4.05	25.24	8.07	0.7743
5	35.16	2.61	35.26	3.48	0.4341

Table 1: 1st floor: Natural frequencies f and damping coefficients ζ for the first five modes.

Mode	f EFDD [Hz]	ζ EFDD [%]	f SSI [Hz]	ζ SSI [%]	MAC EFDD-SSI
1	7.36	4.13	7.36	4.20	0.9996
2	10.04	2.32	9.94	7.20	0.9664
3	11.07	2.03	10.96	3.24	0.8177
4	12.73	2.41	12.75	2.45	0.9821
5	15.72	2.62	15.66	2.61	0.9912
6	17.71	2.75	17.70	3.11	0.9919
7	20.13	1.65	20.22	3.48	0.9771
8	26.34	2.48	26.24	16.05	0.7785

Table 2: 2nd floor: Natural frequencies f and damping coefficients ζ for the first eight modes.

Mode	f EFDD [Hz]	ζ EFDD [%]	f SSI [Hz]	ζ SSI [%]	MAC EFDD-SSI
1	11.89	3.33	11.81	3.74	0.9987
2	14.20	2.37	14.33	8.76	0.8614
3	15.74	2.54	15.85	2.68	0.9451
4	18.17	2.05	18.11	6.43	0.8484
5	21.43	2.59	21.41	4.44	0.9662

Table 3: 3rd floor: Natural frequencies f and damping coefficients ζ for the first five modes.

The MAC-values (Modal Assurance Criterion) given in the Tables 1 to 3 compare the mode shapes as calculated with EFDD and with SSI respectively. MAC ranges between 0 and 1, MAC = 1 indicating that the two eigenvectors compared are identical.

The shapes of the first modes of floors No. 1 to 3 are given in the Figures 6 to 8. Figures 9 and 10 show the second and third mode of the 2nd floor.

The fundamental frequency of the 4th floor was evaluated to f = 12.0 Hz.

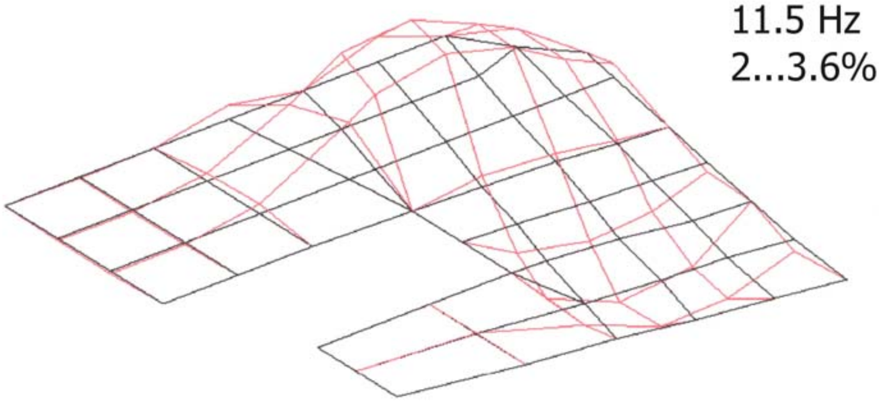

Figure 6: 1st floor, Mode 1

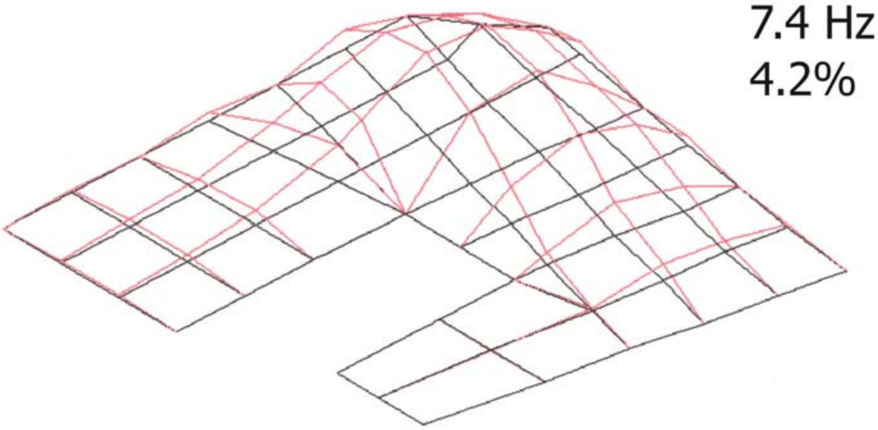

Figure 7: 2nd floor, Mode 1

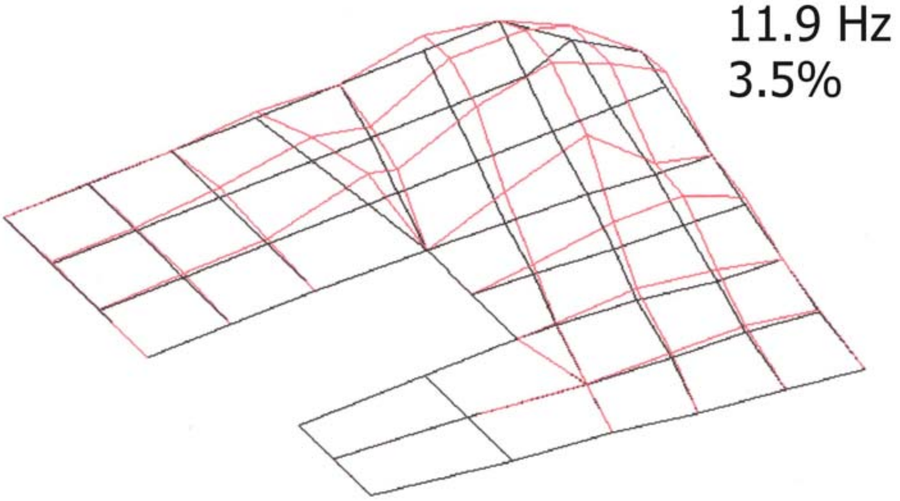

Figure 8: 3rd floor, Mode 1

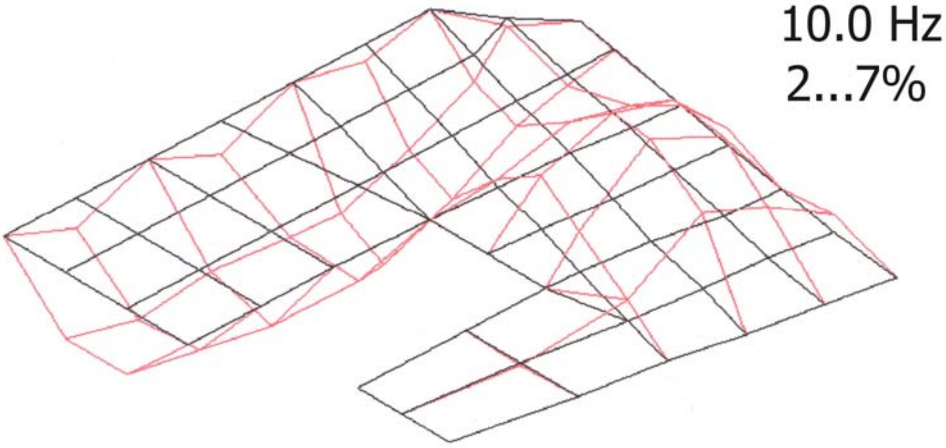

Figure 9: 2nd floor, Mode 2

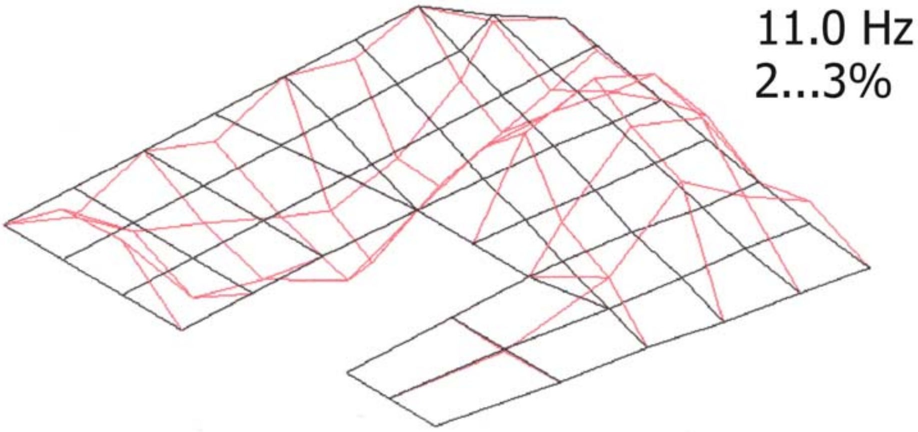

Figure 10: 2nd floor, Mode 3

4 Vibration Monitoring

4.1 Instrumentation, data acquisition

To identify the source of the vibrations of the 2nd floor slab, a triaxial velocity sensor was mounted at a critical point. The vibrations were monitored for two months (December 19, 2003 to February 26, 2004) using a newly developed internet-accelerograph, IA-1. The instrument originally has internally mounted accelerometers, but a modified version was deployed with an external GSV-310 velocity sensor for this monitoring project (Fig. 11).

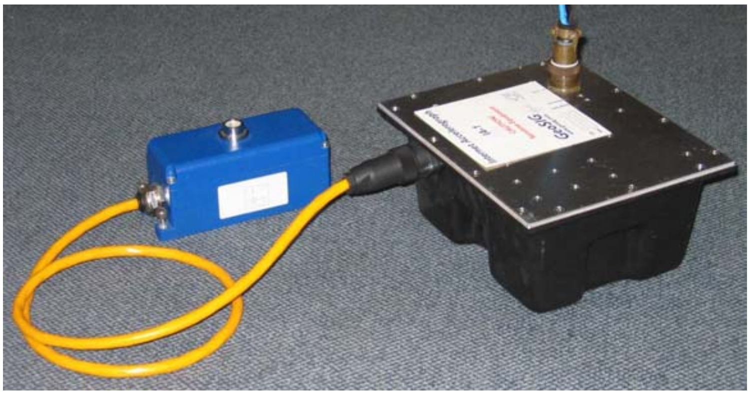

Figure 11: IA-1 with external velocity sensor, used for vibration monitoring.

The three signals were continuously sampled at a rate s = 100 Hz and stored every five minutes in a file on the IA-1 local disk. This disk is large enough to store the signals collected for 2.5 days.

Every day, the 288 data files were transferred via internet to a remote server. This internet connection also allowed to check each of the 5-minute-files immediately after it had been saved to the local disk from any given point in the world having internet access (and the necessary security permissions to reach to the internet accelerograph). Application of this procedure was facilitated very much through the fact that the IA-1 could be hooked-up to the local intranet available in the office building under investigation.

4.2 Signal processing

Using the GeoDAS software package, for each 5-minute time window a number of characteristic values could be determined within seconds. These values cover several types of maximum and averaged values as well as the dominant frequency.

4.3 Results

Figures 12 to 15 show the peak values of all 288 5-minute-time windows of the vectorial velocity as a function of time for a 24-hours monitoring time. Diagrams of this type were calculated on a daily basis and were used to get a first insight into the behaviour of the floor under investigation. The behaviour as shown in the Figures 12 to 14 can be called "typical" and covers almost all of the 64 days of undisturbed 24-hours monitoring. These "typical" diagrams, identically scaled on the ordinate, include a normal working day (Fig. 12), a typical Sunday (Fig. 13) and a typical Saturday (Fig. 14).

Figure 15 shows the diagram for a normal working day with one singular event. It was not possible to identify the source of this singular event. Probably, somebody "stumbled" over the velocity sensor.

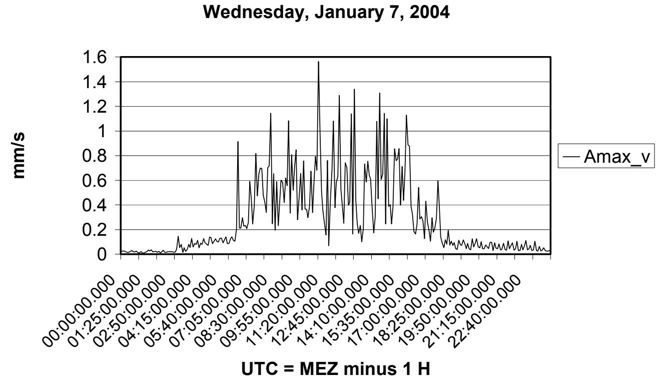

Figure 12: Floor vibrations for a typical normal working day.

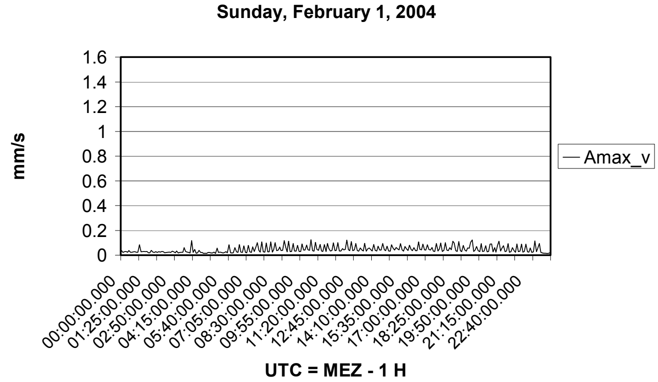

Figure 13: Floor vibrations for a typical Sunday.

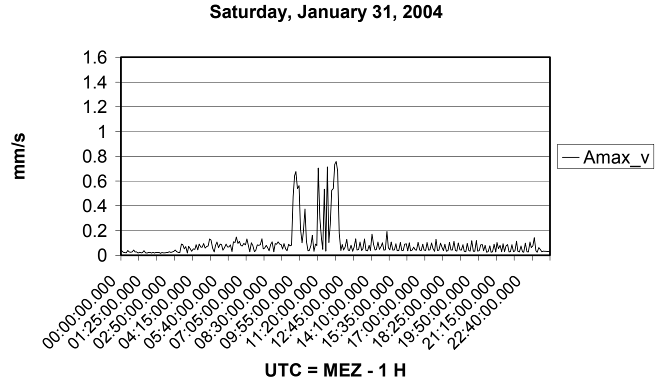

Figure 14: Floor vibrations for a typical Saturday.

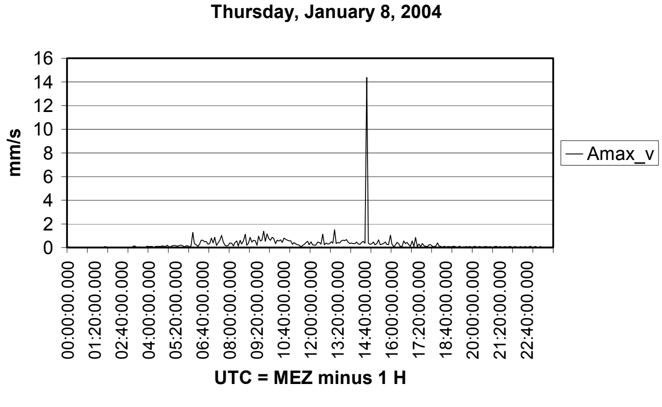

Figure 15: Normal working day with a singular event.

Therefore, as a first result of the monitoring tests, it could be noted that no other source could be identified than people walking on the floor.

Many people walking on the floor resulted in maximum vectorial velocity amplitude values in the range $a_{max}v$ = 0.8…2.5 mm/s (1.34 mm/s on the average).

No people present in the building (typical Sunday) resulted in $a_{max}v$ = 0.10…0.22 mm/s (0.17 mm/s on the average).

Some people walking on the floor (typical Saturdays, one or two people present, mainly the room cleaning team) resulted in $a_{max}v$ = 0.4…2.0 mm/s (0.94 mm/s on the average).

An additional test was performed with making one person jump for two minutes in the neighbourhood of the velocity sensor. This yielded a peak value $a_{max}v$ = 6.2 mm/s or roughly three times the value of normal walking on the floor and definitely less than what was measured for the "singular" event mentioned above.

5 Discussion of the floors' dynamic characteristics

As can be taken from [1]and[2], problems with concrete floor vibrations excited through walking people can be expected if $f < 7.5$ Hz.

This easily explains the fact that problems were encountered with the 2nd floor but not with the other floors.

Two remarks can be added here.

a) The stiffening action of floor-to-ceiling walls located on top of a concrete floor is obviously much more important than their mass effect. There is no other explanation for the 3rd floor fundamental natural frequency being a factor of 1.6 higher than the one of the 2nd floor (with exhibiting an almost identical mode shape!).

b) It is interesting to note that the fundamental mode of the "clean" 2nd floor exhibits higher damping values than the ones of the 1st and 3rd floors. Both, the 1st and 2nd floors have no floor-to-ceiling walls, but they have several partitioning "cardboard" walls with a height of some 0.3 m less than the room height. As a matter of speculation (and may be considering the shape of the respective fundamental mode) these partitioning walls contribute better to the damping capacity of the 2nd floor than to the one of the 1st floor (the 3rd has no "cardboard" partitioning walls).

6 Rating of the 2nd floor vibration levels

6.1 Perceptibility

According to [1], perceptibility of human beings to vibration is proportional to acceleration for $f = 1…10$ Hz and proportional to velocity for $f = 10…100$ Hz. Staying with velocity, the threshold of perceptibility is 0.16 mm/s, $v > 0.64$ mm/s means "just perceptible", $v > 2.0$ mm/s means "clearly perceptible", and $v > 6.4$ mm/s means "disturbing/unpleasant". Transforming the measured velocities into acceleration based on a dominating frequency $f = 7.4$ Hz and applying the respective thresholds given yields the same results as for the velocity values:

a) the vibration level measured without presence of people is close to the threshold of perceptibility,

b) the vibration level measured for normal working conditions is mainly between the levels "just perceptible" and "clearly perceptible".

6.2 Acceptability

The German standard [3] which is widely used in Europe can be applied to vibrations in residential buildings only.

The measured vibrations were therefore rated according to the ISO-Standards [4] and [5]. This rating is based on measured RMS-values of acceleration or velocity. Processing the signals using the GeoDAS software package allowed to plot similar graphics as shown in the Figures 12 to 15 for RMS- instead of peak values (Fig. 16).

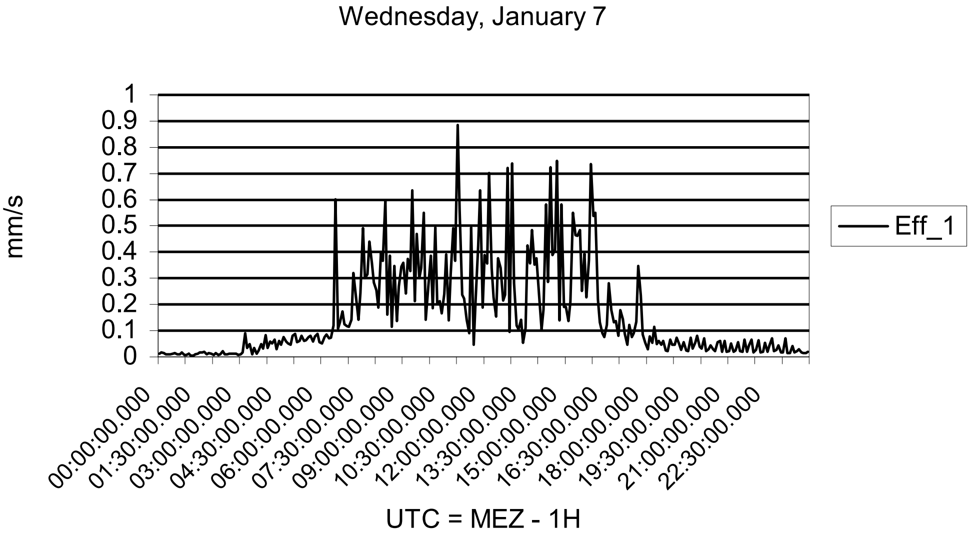

Figure 16: Floor vibrations for a typical normal working day.

The values for the two cases of interest are

a) normal working day: v_{RMS} = 0.47…1.45 mm/s, 0.8 mm/s on the average,

b) nobody present: v_{RMS} = 0.07…0.17 mm/s, 0.11 mm/s on the average.

Three parameters have to be taken into account when applying ISO 2631 ([4] and [5]).

a) the frequency weighting curve (Fig. 17),

b) the base curve (Fig 18), and

c) the multiplication factor.

The frequency weighting curves take care of the fact that the sensibility of humans against vibrations depends on the vibrations' direction and frequency. For vertical vibrations with a dominant frequency f = 7.4 Hz, the frequency weighting is 0 dB.

The base curve yields that for vertical vibrations with f = 7.4 Hz, the base value is v = 0.1 mm/s.

For office buildings, "continuous or intermittent vibration", "day" and "night", Table 2 of [5]gives a multiplication factor 4. Multiplying this factor with the base value yields, that vibration levels (RMS velocity) of v < 0.4 mm/s "have been found to be satisfactory".

In summary: During working hours, the vibration level is up to 3.6 times higher than "satisfactory" according to [4], [5]. The vibration level valid for the state "nobody present in the building" is well below the "satisfactory" level according to ISO 2631.

At the moment, discussions are ongoing to find an optimum solution for the problem.

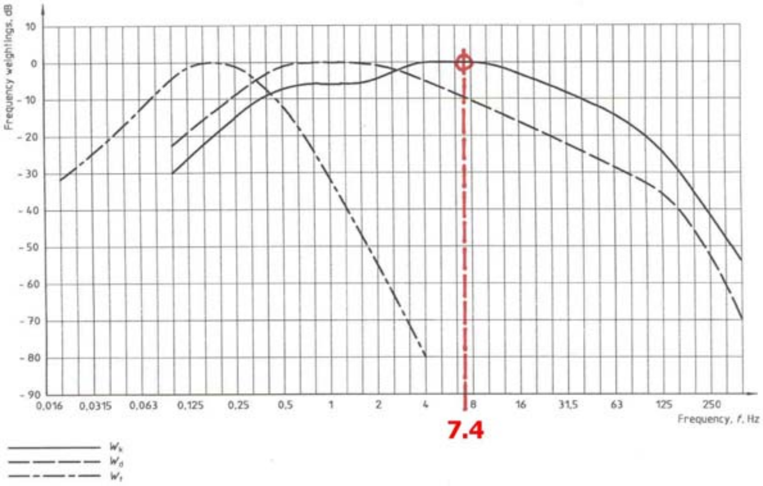

Figure 17: Frequency weighting curves as given in [4]. W_k (solid line) applies for vertical movement.

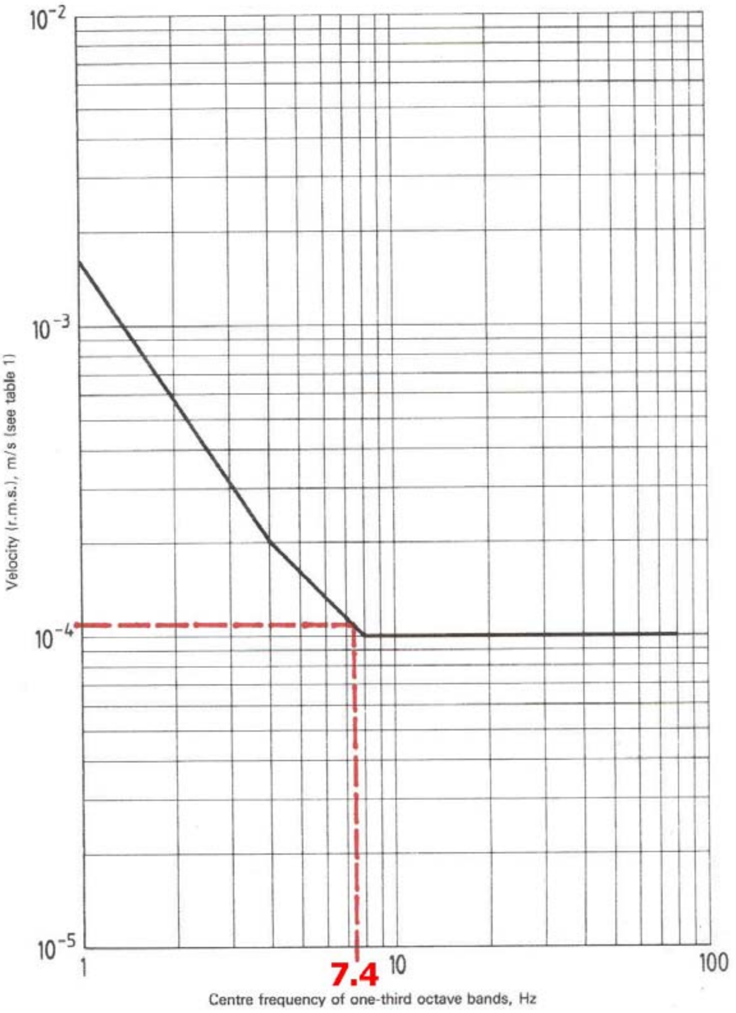

Figure 2b — **Building vibration** ***z*****-axis base curve for velocity**
(this represents the foot-to-head vibration base curve, see 4.2.1)

Figure 18: Base value for f = 7.4 Hz (ordinate's scaling: m/s).

7 Conclusions

As the primary result, the investigation discussed here shows that a lower frequency limit $f = 7.5$ Hz for the fundamental natural frequency of concrete slabs in office buildings is not conservative.

Furthermore, the investigation showed that the presence of "non-load-carrying", secondary floor-to-ceiling walls on top of a slab significantly influences the slab's dynamic characteristics. The stiffening effect of such walls seems to be much larger than their mass effect.

Finally: The presence of lightweight partitioning walls with a height of less than the room height seems to (positively) influence the damping capacity of the slab.

Acknowledgements

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