Chapter 6
Vibration Testing of a Floor During Multiple Phases of Construction

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Abstract It is often difficult to conduct modal testing and response measurements during the construction of civil structures. This is a result of both the time requirements and accessibility, both of which limit the opportunities available for testing. Clean measurement data can sometimes be difficult to obtain due to disturbances on site from other construction activities. This paper presents the results from a unique opportunity to conduct full modal tests on a lightweight office floor during renovation for adaptive re-use. Originally a warehouse facility, the building renovation involved adaptation to executive office spaces. This included renovation of a lightweight mezzanine floor area that would house senior management staff. The author was provided the opportunity to measure the floor in a bare (unfinished) state, followed by partial and complete fit-out conditions. Footfall response measurements were conducted along two distinct walking paths during each phase so that the variations in floor response could be quantified at key locations. The modal and footfall response tests were correlated to finite element models of the floor for evaluation of finite element and footfall force modeling techniques. The results from the study provided insight on finite element modeling techniques and the effects of finishes and other non-structural elements on the dynamic characteristics of the floor.

Keywords Floor vibration • Footfalls • Model correlation • Modal testing • Impact testing • Partitions

6.1 Introduction

During the vibration design of a floor the analyst often has to make assumptions regarding the contributions of non-structural elements to the dynamic response (e.g., partitions, services, furniture). The currently recommended approach is to introduce mass and damping to the system that accounts for the effect of these elements on response reduction [1–3]. Although it is generally recognized that some partition designs can contribute significant stiffness to the system, a reliable approach to modeling these effects has not been made available and remains a topic of current research [4, 5].

Field studies are essential for quantifying the effects of non-structural elements on floor dynamics and performance. Quantifying these effects requires measurement of a floor during various phases of construction so that changes to the dynamic properties can be tracked. However, this approach can be a challenge due to cost, time requirements, and construction schedules, all of which lead to difficulties with accessibility. Typically, measurements are conducted after hours in a quiet setting so that good quality data can be acquired free from contamination.

In this paper we present the results from a unique opportunity to assess the vibration performance of a floor during three phases of construction: bare floor (post-demolition), partial fit-out and occupancy. At the time of the study the warehouse facility was undergoing renovation to executive office space. Early in the renovations the author noted considerable discomfort from footfalls on a small area of mezzanine floor that was planned to house executive offices. Access was granted to conduct modal surveys during each of the three phases, which included footfall response measurements to quantify performance of the floor. Some details regarding model correlation and updating related to the bare floor condition were presented at IMAC XXXI [6].

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6.2 Description of the Floor

Photos of the test floor, taken during demolition and partial fit-out, are shown in Fig. 6.1. Figure 6.2 is the final layout of the office space, and ground floor area below. This particular area of the building houses executive office space, with the office's senior executive located at the northeast corner of the mezzanine floor. The space is favored architecturally due to the free edge along grid line B, which allows occupants of the offices to look out over the area below. The servery extends below the mezzanine area (as shown at right in Fig. 6.2), and due to its function must remain mostly open. The few wall partitions located at level one are mostly full-height (slab-to-slab) concrete masonry construction.

During an early visit to the site to conduct acoustic testing, it was noticed that the subject floor was particularly lively. Although this liveliness could be expected in its unfinished state, a review of final layouts indicated that sufficient mass and damping may not be available to limit the response of the floor once occupied. An assessment scope was developed to predict performance following fit-out and establish if mitigation measures would be necessary. The author was granted access to the floor during three phases of construction to measure changes in the dynamics, for incorporation in the assessment process in advance of completion.

The final floor layout, shown in Fig. 6.2, includes demountable (partial height) wall partitions across most of the floor. The only walls extending slab-to-roof above are those in the northeast office and the conference room at the south end.

The floor framing consists of 64 mm thick concrete on 38 mm corrugated steel deck. The slab is supported by open-web steel joists of depths varying between 350 mm (22-in.) and 375 mm (24-in.), spanning in the north–south direction. The floor

Fig. 6.1 Photos of the test floor during early renovation/demolition (*top*) and partial fit-out (*bottom*)

Fig. 6.2 Final floor layouts, mezzanine (*left*) and servery below (*right*)

system is supported on columns at 9.14 m offsets in the project north–south direction (vertical alignment to the page) and 6.1 m offsets in the project east–west direction. Masonry block walls support portions of the floor along grid lines 2 and 3. A block wall also supports the floor from below, in the project east–west direction approximately 2 m north of gridline 5, as seen from the layout of level one. As a result, the bay spanning between grid line 6 and this wall has a span of approximately 11.14 m (compared with the 9.14 m span of other bays).

Original drawings of the floor do not exist and the dimensions of all framework, boundary conditions and section designations had to be gleaned from visual inspection and measurements at the site.

6.3 Dynamic Testing Program

Access to the floor was permitted after hours to conduct dynamic testing during each of the three phases of construction. This included modal testing of the floor and footfall measurements for assessment of vibration performance. A brief description of the conditions of the floor during each phase is as follows:

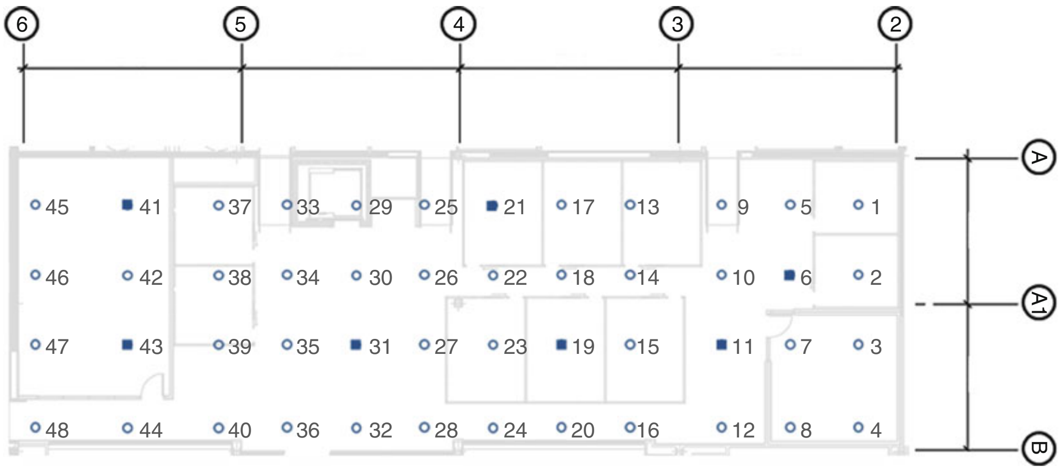

Fig. 6.3 Impact test grid layout (measurement points shown as *filled squares*)

Phase 1, Post Demolition:	Unfinished floor, exposed structure beneath, no services, staircase, ramps or wall finishes in place
Phase 2, Partial Fit-Out:	Un-finished floor, finished drywall ceiling below, full-height cavity (double wythe) wall partitions at south edge conference room and north edge office, MEP services installed below, staircase, ramps and perimeter gypsum board walls in place
Phase 3, Occupancy:	Finished space consisting of carpet and ceramic tile flooring, demountable interior office partitions (terminating at finished lay-in tile ceiling grid), lightweight 'modern' office furniture, all services and fixtures in place

Details on the testing program are discussed below. Acquisition parameters were set equal for all three test programs so that equivalent processing techniques could be applied.

6.3.1 Modal Testing

Given the light weight and liveliness of the floor, impact testing was selected as a suitable methodology for the modal tests. A total of 48 test points were specified (4×12 grid), so that a high degree of spatial resolution could be achieved for mode shape visualization. An 8-channel acquisition system was employed for data collection. Channels 1–7 were used to record floor accelerations using a combination of three seismic accelerometers (10 V/g sensitivity), and four general purpose units (1 V/g). Channel 8 was dedicated to the modal hammer. The test grid layout is shown in Fig. 6.3. Additional sensors were employed for redundancy to ensure that multiple data sets could be analysed during Phase 1. Only four sensors were deployed for Phases 2 and 3 at grid points 11, 19, 31 and 43.

6.3.2 Footfall Testing

Measurements of the footfall response of the floor were conducted during each site visit. The sensor layout for Phase 1 and walking paths selected are shown in Fig. 6.4. During Phases 2 and 3 measurements were conducted at grids 3, 5, 15 and 17 only. The walking paths were selected based on final layouts and measured during each of the three site visits so that meaningful comparisons could be made. Gait frequencies were specified based on fractions of the field-identified floor modes to invoke resonance. The pacing rates selected to excite these modes were in the range of 87–120 steps per minute

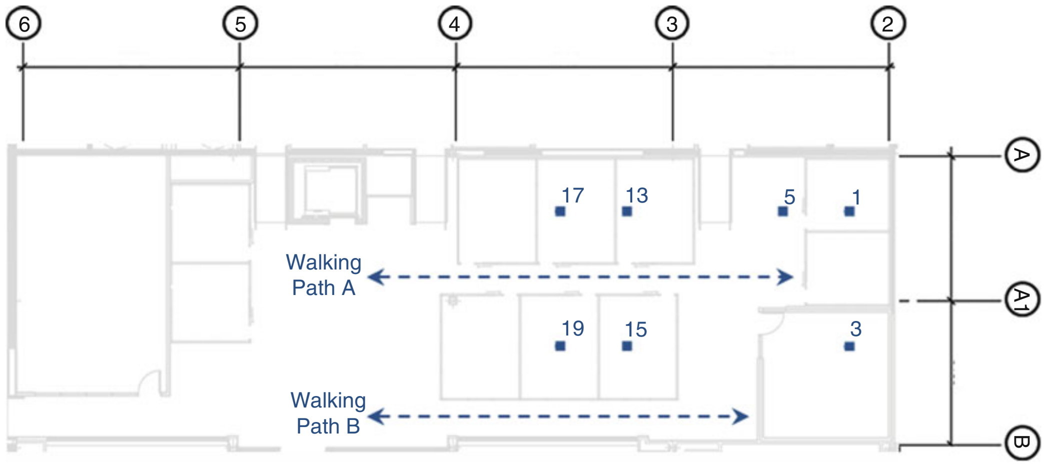

Fig. 6.4 Footfall test grid layout (measurement points shown as *filled squares*)

(1.45–2 Hz). In the author's experience pacing rates in the range of 90–110 steps per minute are comfortable and reasonable for an office environment. Even with the use of a metronome the 87 and 120 steps per minute pacing rates were considered awkward and were not expected to be a regular occurrence in the occupied setting.

During the tests a metronome was set to the specified pacing rate and the test subject walked along the prescribed walking paths ('A' and 'B' in Fig. 6.4). Two trials were conducted by two individuals at the site, for a total of four walking trials per pacing rate. The walker weights differed by 22 kg (50 lbs), and the same individuals conducted all three site visits. Interestingly, the heavier walker did not always result in greater response. This could be attributed to superior synchronization of the lighter walker in some cases.

Following the site visit the raw time data were filtered using the ISO *k* weighting filter corresponding to z-axis vibrations (the shape of the filter is the inverse of the ISO base curve for human perception) [7]. The sliding 1-s RMS value of the weighted time history was computed to establish the maximum RMS acceleration level. The response factor *R* was then computed as the ratio of the maximum 1-s weighted RMS acceleration divided by the base curve value of 0.005 m/s^2. This is a common approach applied in Europe and currently being adopted by some consultants in North America.

6.4 Results

6.4.1 Mode Indicator Functions

Figure 6.5 is the Mode Indicator Functions (MIFs) for Phases 1 through 3. The bare floor MIF shown in black indicates a high modal density in the 6–15 Hz range. This is an exhibition of the plate-like dynamics of the floor during the Phase 1 tests, as well as non-linearity in the test data resulting from the liveliness of the floor.

Comparing the MIFs for Phases 1 and 2 (blue and black curves in the left plot), it is clear that the introduction of the stairwell, ramps and partition walls resulted in an upward shift of modal frequencies, due to an increase in stiffness. Damping appears to have increased slightly and many of the spurious peaks present on the bare floor have smoothed into distinct modes.

Finally, comparing the MIFs for Phases 1 and 3 (blue and black curves in the right plot), there is a clear increase in damping as exhibited by the width of the peaks compared to Phases 1 and 2. There is also a significant reduction the modal density, with only four distinct peaks present in the data below 15 Hz. Interestingly, the fundamental mode of the floor shifted back to almost precisely the bare floor value following fit-out. This coincidence is a result of the right balance of increased mass from the furnishings and fixtures, and increased stiffness from the non-structural elements. More details are discussed below.

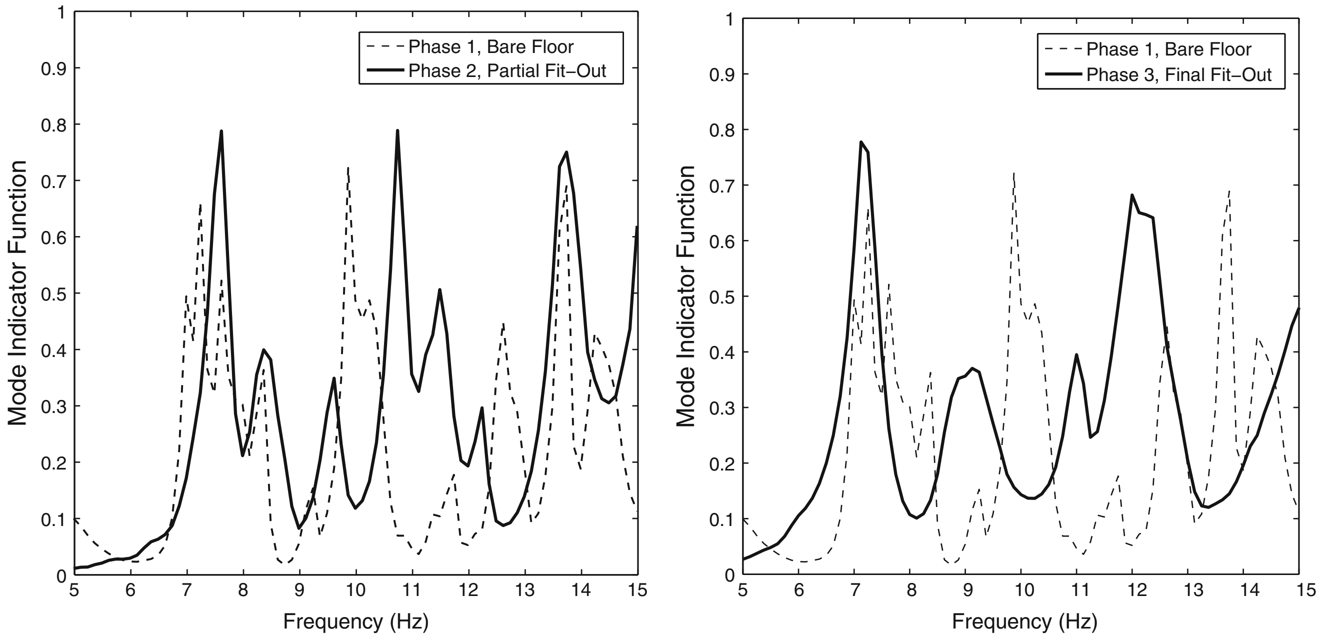

Fig. 6.5 MIFs measured during each of the three phases of construction (color figures online)

Table 6.1 Summary of identified frequencies for the first five modes in each phase of testing

	Identified Frequency (Hz)		
Mode No.	Phase 1 Bare Floor	Phase 2 Partial Fit-Out	Phase 3 Occupancy
1	7.0	7.6	7.3
2	7.3	8.4	8.1
3	7.6	9.0	8.9
4	8.0	9.7	9.2
5	8.3	10.7	9.3

6.4.2 Identified Modal Parameters

Identification of modal parameters (frequencies, mode shapes and damping ratios) was performed using both time and frequency domain techniques. These included the Eigensystem Realization Algorithm, Stochastic Subspace Identification, the Rational Fraction Polynomial method and the Poly-reference Least Squares Complex Frequency method. Identification results that were consistent among several methods were generally regarded to be actual modes and spurious results were discarded. Common mode indicator functions were also used to separate noise modes from structural modes.

The first five modal frequencies and damping ratios, identified with confidence for each phase, are listed in Tables 6.1 and 6.2. The highlighted values are associated with the first significant mode of the floor, which turned out to be the ‘problem mode’ as discussed later in the paper. As expected, there identified damping increased as the floor progressed through fit-out. An approximate doubling of identified damping was observed in Phase 2, and damping in Phase 3 is approximately three times that of the bare floor. Worth noting is the damping ratios for the occupied floor are in the range of 4–5 %, which is consistent with other case studies from the literature and the design guidance for dynamic analysis of floors [1–3, 8].

Figure 6.6 is the mode shapes for the first three modes of the floor during each of the three phases of testing. Some notable observations from these results are the disappearance of Mode 1 of the bare floor for the Phase 2 configuration, which then reappeared in Phase 3. This may be a result of poor excitation and inability to identify this mode from the Phase 2 test data. The presence of additional stiffness from the renovations is exemplified by the deflected shape of the fundamental bending mode at 7.3 Hz (7.6 Hz in Phase 2). The restraint provided by the wall finishes and ramps are evident along gridline A, particularly when comparing Phases 1 and 3. The effect of the staircase at coordinate B4.5 can also be observed, with reduced motion at this location in this mode in Phases 2 and 3 (Fig. 6.6).

Table 6.2 Summary of identified damping ratios for the first five modes in each phase of testing

	Identified Damping (% critical)		
Mode No.	Phase 1 Bare Floor	Phase 2 Partial Fit-Out	Phase 3 Occupancy
1	1.4	2.2	4.5
2	0.9	2.3	4.2
3	1.6	2.2	4.4
4	1.7	2.8	4.3
5	0.9	1.8	2.9

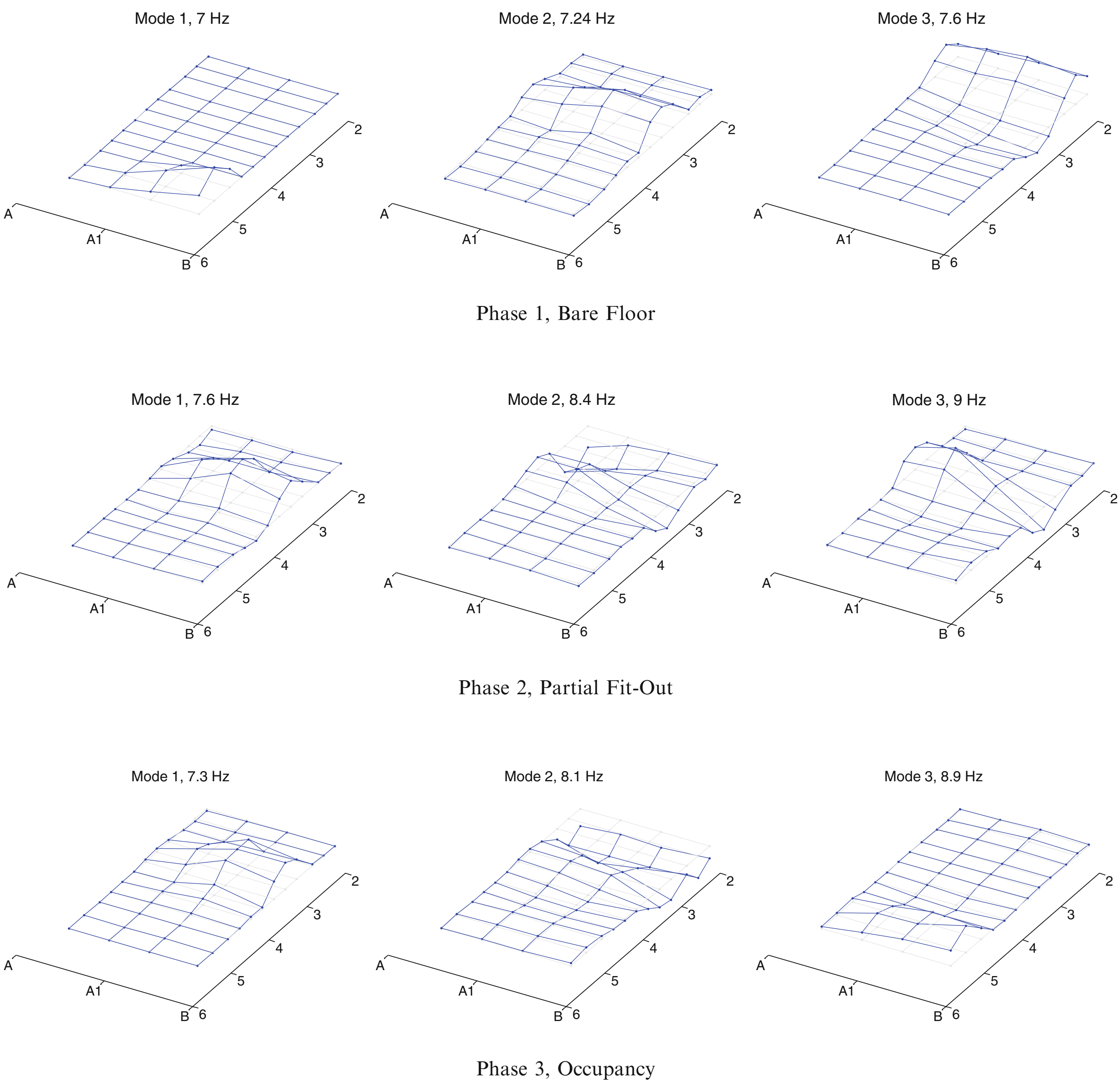

Fig. 6.6 Identified mode shapes for the first three modes of the floor

Table 6.3 Maximum measured R factors

		Maximum measure R factor			
Testing phase	Walking path	Grid 3	Grid 5	Grid 15	Grid 17
1	A	8.5	11.6	8.4	41.5
	B	5.7	16.6	16.6	30.3
2	A	1.4	6.6	10.2	4.5
	B	0.9	3.9	6.1	10.3
3	A	1.4	6.6	3.7	2.3
	B	1.4	1.1	2.4	5.1

Table 6.4 Relative change in R factors during renovation

		R factor change			
Relative change	Walking path	Grid 3 (%)	Grid 5 (%)	Grid 15 (%)	Grid 17 (%)
Phase 1–2	A	−84	−43	22	−89
	B	−84	−77	−63	−66
Phase 2–3	A	2	1	−63	−48
	B	59	−71	−61	−50

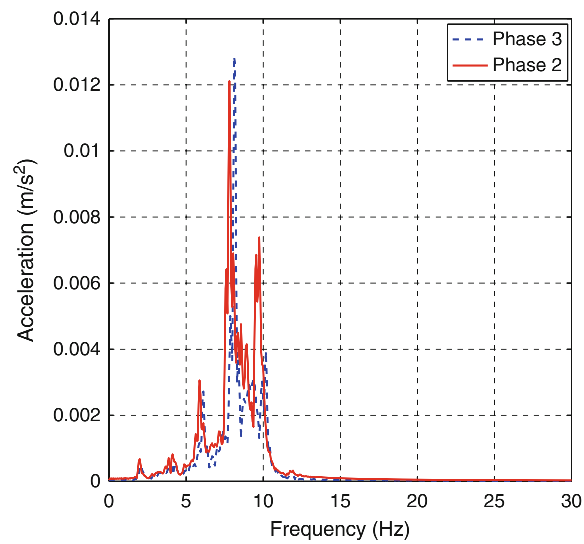

Fig. 6.7 Footfall responses at grid 5 measured during Phases 2 and 3

6.4.3 Footfall Response Levels

Footfall responses were measured during each phase of construction at floor locations corresponding to offices in the final layout. The purpose of the tests was to: (1) evaluate forcing models in the literature and (2) assess the performance of the floor once constructed. Evaluation of forcing models was conducted using a finite element model developed based on the identified modal parameters of the bare floor. Details from that portion of the study are presented in [6].

The footfall tests were conducted using a range of gait frequencies selected to excite the floor in a resonance. The frequencies were determined from the measured FRFs while on site and included a range between 87 steps per minute (1.45 Hz) and 120 steps per minute (2 Hz). The maximum measured R factors for each walking path and grid location are summarized in Table 6.3. Note that an R factor of 2–4 is recommended by the ISO for office areas (the lower limit being applicable to quiet or executive offices). The relative changes in R factors resulting Phase 1–2 and Phase 2–3 are listed in Table 6.4.

Consistent reductions in response were measured at grid locations 15 and 17 as the floor transitioned from its bare state to the fit-out condition. In some cases there were increases in the R factor values, which are likely a result of variability in the excitation, rather than degradation of dynamic performance of the floor. Interestingly, the R factors at grids 3 and 5 did not change following the transition from Phase 2 to Phase 3 for excitation along walking Path A. One possible reason can be deduced from the spectra associated with these events (Fig. 6.7). The peak responses for each event are associated with the first two modes of the floor (see Fig. 6.6), which remained relatively unchanged upon completion of the renovation.

It is worth mentioning that although R factors as high as 8 were measured on the floor following occupancy (grid point 19), and that even though the authors experienced discomfort while seated in the office during the tests (and also noted visual cues such as moving computer monitors and shaking water in a bottle on the desk of one office), there have been no complaints

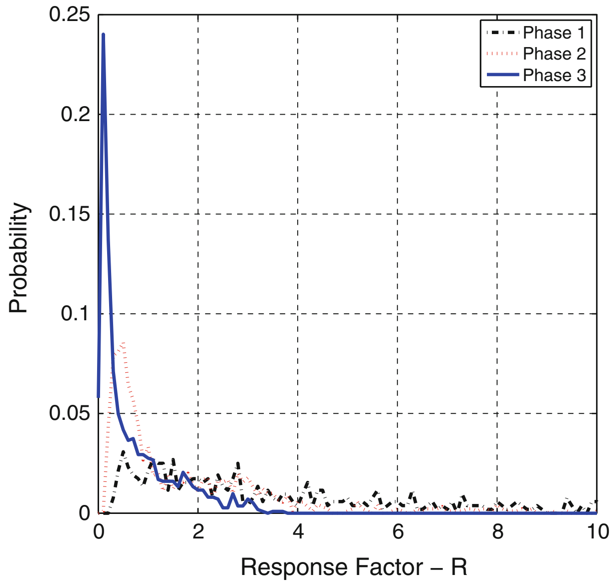

Fig. 6.8 Distributions for footfall data measured at grid point 17 for each of the three testing phases (color figures online)

with respect to floor motions since occupancy began. This is a practical example of the subjectivity associated with floor vibration and human comfort. Perhaps the occupants are willing to tolerate the vibrations, or perhaps on a day-to-day basis there is limited foot traffic in this area of the building.

The results also bring to question the practicality of assessing performance based on maximum response metrics (e.g., maximum R factors or 1-s RMS levels, peak acceleration etc.). The use of a time window greater than 1-s in the RMS calculations would certainly result in lower R factors. Alternatively, a more rigorous statistical review of the data could be applied. Such an approach was presented by Živanović and Pavić [9], and involves processing of the time-varying R factors in a statistical framework by constructing histograms of the 1-s sliding window R factors. These histograms can then be used to construct the cumulative distribution functions to examine the cumulative probabilities, and hence the return periods, associated with a given R factor. Such an approach not only permits assessment of measurement data, but is also useful for comparisons of different floors, stages of construction, mitigation scenarios etc. In the context of ultra-sensitive research environments, where the design is driven by equipment functionality rather than occupant comfort, this approach permits critical assessments of response measurements/predictions against the time dependent sensitivity of various equipment (e.g., imaging).

Figure 6.8 is an example applied to the footfall measurements at grid 17 for each of the three testing phases. The differences in the distributions of the measurement data are immediately apparent. The sample PDF (shown at left), illustrates the clustering of R factors for each phase. The majority of data are clustered at R values less than one for this grid point during Phase 3 (blue curve), whereas there is scatter across the range (somewhat uniform density) in the bare floor condition (black curve). The CDFs for the three data sets (shown at right), quantify the return periods associated with the R factors. For example, 80 % of the time an R factor of 8 was measured on the bare floor, compared to an R factor of 1 for final fit-out.

Plots of the distribution functions for the maximum measured response location following occupancy (grid point 19), are shown in Fig. 6.9. Although the maximum measured R factor at this location was 8, a statistical review of the data illustrates that 80 % of the time the R factor at this location is 2 or less. Collection of more data during a typical work day at this location would provide more definitive conclusions. Nonetheless, these examples illustrate the importance of considering the temporal variation in responses when assessing suitability of a design or existing floor.

6.5 Concluding Remarks

Measurements conducted on floor during multiple phases of construction are important for quantifying changes to dynamic properties and overall floor performance. The results from this study can be applied to the analysis and assessment of floors undergoing renovations or adaptive re-use, where it is important to quantify existing and expected future performance. Caution should be exercised in the use of maximum response estimates during assessment as this can be overly conservative, resulting in over-design. Statistical analysis of the data is recommended for quantification of the temporal variations in response.

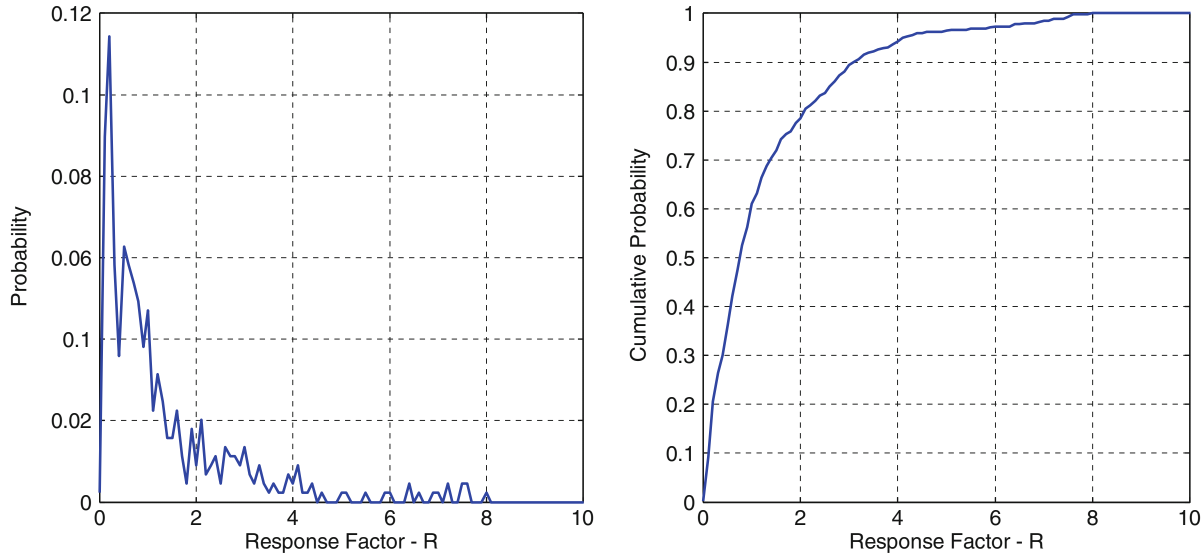

Fig. 6.9 Distributions for footfall data measured at location 19 following occupancy of the floor

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