# Relative Acoustic Performance of Prefabricated Steel Stair Assemblies©


Christopher Higgins, PhD, PE
Professor
and
Duncan Stark
Graduate Research Assistant


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**School of Civil and Construction Engineering**
Oregon State University, 101 Kearney Hall
Corvallis, Oregon 97331-2302
**T** 541-737-4934 | **F** 541-737-3052 |
http://cce.oregonstate.edu

## Background

Prefabricated steel stair assemblies are commonly used in industrial, commercial, and residential applications. In some situations, stairways can be a source of noise that can adversely affect the comfort of occupants in adjacent areas. Generally, steel stairs with concrete filled pans have been considered quieter than steel tread covered stairs. However, concrete filled pans are more expensive, must be protected during construction, and can require remediation if cracked or damaged before occupancy. The purpose of the present research was to quantify the relative acoustic performance of different stair treatments under different mechanical inputs. Six different stair treatments were investigated. These included:

1) Traditional concrete filled pan stairs
2) Traditional steel checkered plate stairs
3) Steel checkered plate stairs with proprietary use of Line-X™
4) Steel checkered plate stairs with proprietary use of Soundcoat™ applied to risers alone
5) Steel checkered plate stairs with proprietary use of Soundcoat™ applied to steps alone
6) Steel checkered plate stairs with proprietary use of Soundcoat™ applied to steps *and* risers

These six single flights of stairs were tested individually and then five were tested with accompanying landings. All stair assemblies were fabricated by the Pacific Stair Corporation with production-run details and materials. The traditional stairs (checkered plate and concrete filled pans) provide the current reference acoustic performance baseline levels. In addition to the individual flights, three landings (one checkered plate, one Soundcoat™, and one Line-X™) were tested in combination with their matching stair flights.

No standardized acoustic testing protocols exist for stair assemblies and national and international standards, including ASTM, ISO 140, British and Australian Standards were surveyed and adapted to develop acoustical performance tests of stairs and stair assemblies. Testing protocols were adapted from the following standards as they apply to this research:

- ASTM E 492-04: Standard Test Method for Laboratory Measurement of Impact Sound Transmission through Floor-Ceiling Assemblies Using the Tapping Machine
- ASTM E 2235-04: Standard Test Method for Determination of Decay Rates for Use in Sound Insulation Test Methods
- ISO 140.6-2006: Acoustics – Measurement of Sound insulation in buildings and of building elements. Part 6: Laboratory measurements of impact sound insulation of floors
- ISO 3741: Acoustics – Determination of sound power levels of noise sources using sound pressure – Precision methods for reverberation rooms

## Reverberation Chamber Description and Acoustic Characteristics

A reverberation chamber was constructed to test the acoustic performance of the stair assemblies. The chamber was designed to reject background noise, allow acoustic reverberations (exhibit low acoustic absorption), and to simulate the geometric conditions of use for prefabricated steel stairs (representative of a stairwell). The chamber floor was a cast-in-place concrete slab and j-bolts were installed to allow attachment of the stair landings. The walls and roof were wood framed with 2x6 lumber and sheathed in ¾ in. thick MDO plywood. Fiberglass insulation was placed between the studs. Epoxy paint was applied to the sheathing to produce a hard surface. As suggested in ASTM E 492, sound diffusion panels employed in order to create a more diffuse sound field within the chamber. Two diffusing panels, also made of ¾” MDO, were hung from the ceiling of the chamber. The inside plan dimensions of the final room were 105 in. by 125 in. and the chamber was 144 in. tall. These dimensions meet the requirements of ASTM E 492 that dimensions not be ratios of small whole numbers and that the ratio of the largest dimension to the smallest be less than two. The total volume of the room was 1094 cubic feet. The chamber is shown in Fig. 1 with the stair and landing setup in place for testing.


Fig. 1- Reverberation chamber with stair and landing assembly, standardized tapping machine, and microphone positions (front door is open).

Data collection was performed with an Iotech Daqbook 2000 data acquisition system employing three DBK4 2-channel dynamic signal input cards. The bias currents were set to 4 mA to drive the microphone preamplifiers. Acquisition, analog to digital conversion, scaling, and data storage was controlled using DASYLab software. The sampling rate was set to 33.333 kHz. Low-pass filter settings on the input cards were set at 10 Hz and the high-pass filters were set at 18 kHz. Six microphones meeting accuracy class 1 defined in IEC 61672 were placed throughout the chamber to measure the sound field. The microphones were model MP201 manufactured by BSWA Tech and were matched with MA201 preamplifiers. An example microphone calibration sheet is shown in Appendix 4.

## Fundamental Modes

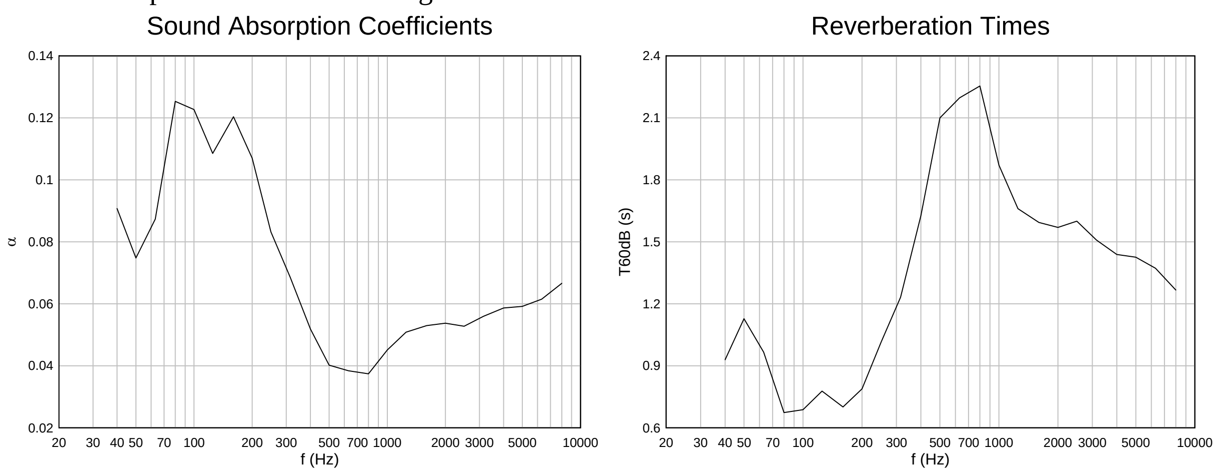
To establish the fundamental modes of the chamber, a constant RMS amplitude sine sweep function was input into a power amplifier which drove a hemi-dodecahedron noise source. The fundamental frequencies of the chamber were identified when the sound amplitude increased at resonance. The theoretical modes were also calculated from the internal dimensions of the chamber using the known speed of sound. Using these two methodologies, the lowest three fundamental modes for the chamber are shown in Table 1.

Table 1- Fundamental modes of reverberant chamber.

| Calculated (Hz) | Measured (Hz) |
|---|---|
| 46.9 | 44.6 |
| 54.1 | 57.2 |
| 64.4 | 68 |

## Absorption and Reverberation Properties

Absorption properties of the reverberation chamber were found by measuring the acoustic response in the room to a decaying sound field. Using a function generator, power amplifier, and hemi-dodecahedron noise source, the room was subjected to loud pink noise (a better approximation of randomly distributed frequencies with respect to the human auditory system). When the sound levels reached steady state, the noise was shut off, and the sound decay was measured. Three of these tests were performed with the noise source at different room locations, and each event was measured by six microphones, giving 18 individual decay measurements (larger than the minimum 15 measurements provided in ASTM E 2235). Third octave band analysis was performed on the decay curves which were then averaged according to ASTM E 2235. A best fit line through the decay curves was found for each frequency band, from which the absorption coefficients, $\alpha$, and reverberation times, T60dB, were calculated for each frequency. The measured responses are shown in Fig. 2 a and b.




a) b)

Fig. 2 - a) Sound absorption coefficients and b) reverberation times in reverberant chamber.

For most of the frequencies of interest, the chamber achieves ISO 140-1 reverberation times of between 1.0 and 2.0 seconds, and ISO 3741 absorption coefficients of less than 0.06. Most importantly, the chamber provides a reference environment that allows repeatable relative comparisons of acoustic performance of the different stair assemblies and acoustic treatments.

**Background Noise**

Tests were conducted to characterize the background noise conditions within the chamber. At the laboratory, there are times that a water pump runs intermittently, while at other times, it is not on. Samples were taken of the background noise under both conditions and third octave analysis was performed as shown in Fig. 3.

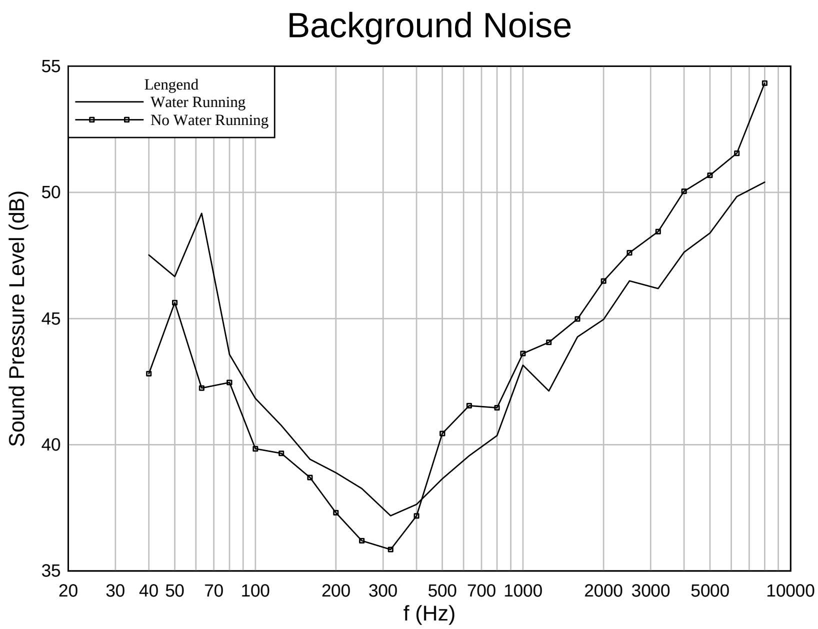



Fig. 3 - Third octave analysis results of background noise conditions inside chamber.

Both ISO 3741 and ASTM E 492 suggest that the background noise levels should be at least 10 dB below the measured sound levels. By comparing this background noise data (either case) with the data collected from the standardized tapping machine (seen in the subsequent section), it can be observed that the difference between the background and test sound levels is over the 10 dB threshold, while the average difference is over 40 dB for all frequencies.

## Stairs Tests

Tests were conducted on each of the six flights of stairs alone (stairs without landings) and then combinations of the flights with the corresponding landings (stairs with landings). These tests and the results are described in the subsequent section.

Tests were conducted at the O.H. Hinsdale Research Laboratory at Oregon State University, on the nights of August 19th and 20th, and during the day of August 22nd (weekend day), 2009. Temperature and relative humidity data for the test periods are shown in Appendix 3. Stairs and landings were installed inside the chamber. The bottom of the stairs rested on the concrete slab and were shimmed where needed to ensure uniform bearing. The stair landings, when used for some test series, were bolted to the embedded j-bolts in the chamber floor.

Data collection for all tests was again performed with the Iotech Daqbook 2010 data acquisition system employing three DBK4 2-channel dynamic signal input cards. The bias currents were set to 4 mA to drive the microphone preamplifiers. Acquisition, analog to digital conversion, scaling, and data storage was again controlled using DASYLab software. The sampling rate was set to 33.333 kHz. Low-pass filter settings on the input cards were set at 10 Hz and the high-pass filters were set at 9 kHz. Six microphones meeting accuracy class 1 defined in IEC 61672 were placed throughout the chamber at a reasonable distance from all surfaces, walls, each other, and the specimen to measure the sound field in the chamber. The microphones were model MP201 manufactured by BSWA Tech and were matched with MA201 preamplifiers and meet ISO 3741 and ISO 140.6 requirements for measuring the sound pressures in the chamber. The microphone locations were kept the same for all specimen types and configurations.

Per ISO 140.6, a BSWA standardized tapping machine, seen in Fig. 4 was used and placed at four locations on each flight of stairs as illustrated in Figs. 5a to d. When the stair landing was used in the tests, the tapping machine was placed at an additional four locations on each landing as seen in Figs. 6a to d. The tapping machine locations were the same for all the different specimens. Walking tests were conducted by having an individual wearing work boots inside the chamber walk up and down the stairs ten times. Drop tests were performed by dropping a five pound hammer from a distance 1 ft above the specimen at the same locations as those used for the tapping machine. Sounds samples of at least 6 seconds duration were collected after the tapping machine achieved steady-state conditions per ISO 140.6. All sampling and data reduction were done in accordance with ISO 3741.

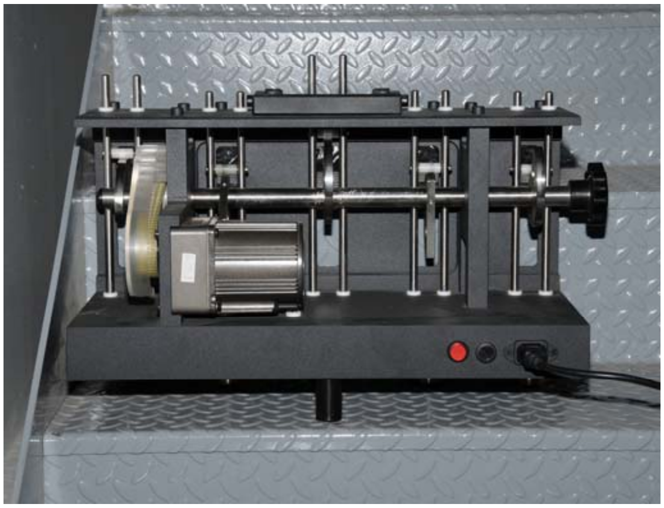


Fig. 4 – ISO Standard tapping machine placed on stair step.

a ($2^{nd}$ step-left)

b ($3^{rd}$ step-center)

c ($4^{th}$ step-left/center)

d ($5^{th}$ step-right)

Fig. 5 – Tapping machine positions on stairs.

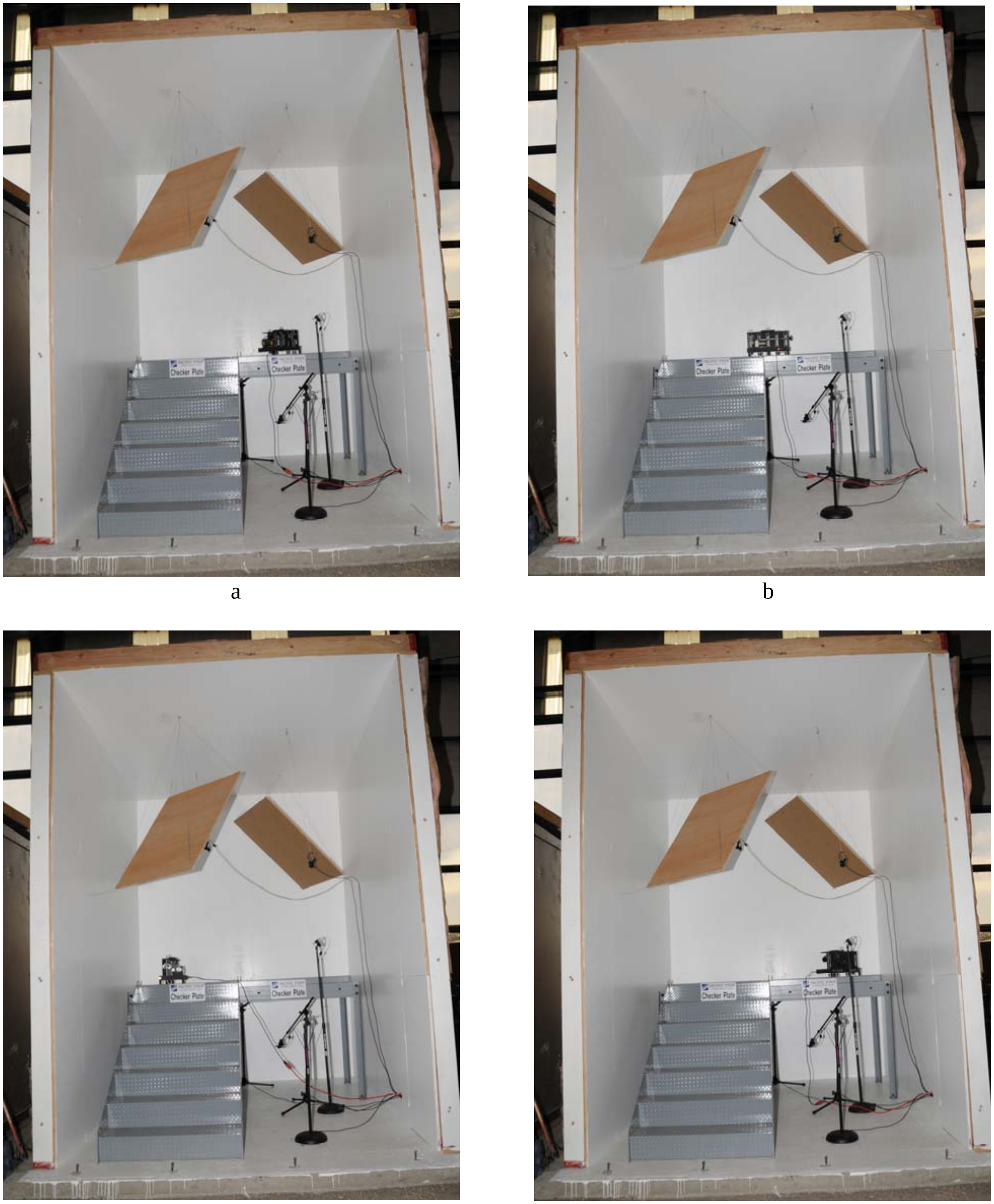


Fig. 6 – Tapping machine positions on landings.

**Results Stairs without Landings**

Each of the six sets of stairs was tested individually, without an attached landing, installed in the same location they occupy when attached to a landing. Tests were conducted using the standardized tapping machine, repeated walking, and dropping a hammer. The sound pressure levels at third octave bands for each of the six sets of stairs were determined from the data collected during these different input test conditions.

*Standardized Tapping Test Results*

Using the sound samples collected from the four different tapping machine locations on the stairs with the six microphone locations, the third octave sound pressure levels were determined as shown in Fig. 7, and numeric values for these and all other graphical data is presented in Appendix 1. The traditional steel checkered plate stair had the highest sound pressures essentially over the entire spectrum. The concrete stairs had the lowest sound pressure levels in the low frequency range, although these frequencies are not typically considered as sources of annoyance. As seen in Fig. 7, over the range of frequencies that the human ear is most sensitive (approximately 1 kHz to 5 kHz) the stairs with Soundcoat™ on the step alone or on both the step and riser produced the lowest sound pressures. Indeed these stairs achieved better performance than the stair with concrete filled pans. Also, as annoying sounds are generally associated with higher frequencies, the improved performance of the Soundcoat™ treated stairs may be of particular benefit. The acoustic performances of the Soundcoat™ treated stairs were about the same whether on the step alone or on both the step and riser. Placing Soundcoat™ on the riser alone achieved performance on par with the Line-X™ coated stair. For practical purposes, use of Soundcoat™ applied to the step alone would achieve the same acoustic performance as the Soundcoat™ on both the riser and step and would provide some economy.

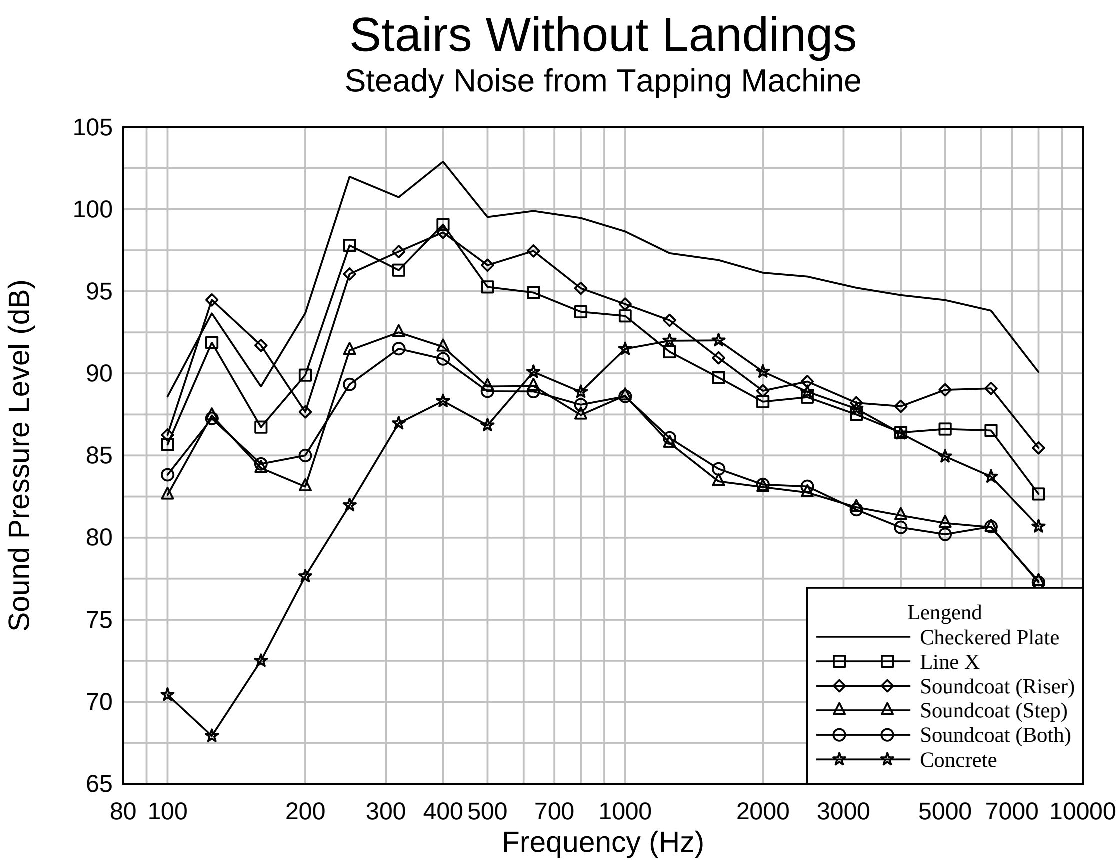



Fig. 7 – Third octave analysis results of standardized tapping tests.

*Drop Test Results*

For the drop tests, the instantaneous maximum pressures resulting from each drop and from each microphone were used. From this data (24 sets per stair assembly) the three largest and the three smallest were discarded, the remaining converted to decibels and averaged according to ISO3741. From these tests, the maximum instantaneous pressures were measured as shown in Table 2.

Table 2 – Maximum instantaneous pressures recorded during hammer drop tests.

| Stairs Alone | |
|---|---|
| Checkered Plate | 122.7 dB |
| Soundcoat™ (Riser) | 120.7 dB |
| Line-X™ | 119.4 dB |
| Soundcoat™ (Both) | 116.5 dB |
| Concrete Pan | 115.5 dB |
| Soundcoat™ (Step) | 115.4 dB |

As seen in Table 2, the traditional steel checkered plate exhibited the highest sound pressure. The Soundcoat™ applied to the step alone and the concrete filled pans had similar performance. The Soundcoat™ applied to both the step and riser resulted in only slightly higher instantaneous sound pressure. This 1 dB difference would not be perceptible to most individuals. Line-X™ was lower than the traditional steel checkered plate but not as low as the stair with concrete filled pans.

*Walking Test Results*

Three sets of walking test data were used for each of the stair assemblies and microphones positions. From each of these (108 total combinations), the instantaneous maximum pressure resulting from each step (12 or 13 per walk test) was noted, providing approximately 1350 total data points. This data was first converted to instantaneous sound pressure levels then corresponding data points for each step were averaged across the six microphones as recommended in ISO 3741. From these values, the two loudest and the two quietest steps in each walk were thrown out, and the remaining steps averaged by the same equations, giving a single value for each walk. The three walks were then averaged, giving a single value for the instantaneous maximum sound pressure levels generated from walking on each set of stairs. The resulting instantaneous peak sound pressure levels are shown in Table 3.

Table 3 – Average instantaneous peak sound pressure levels from walking tests.

| Stairs Alone – Walking | |
|---|---|
| Checkered Plate | 98.7 dB |
| Line-X™ | 90.8 dB |
| Soundcoat™ (Riser) | 89.7 dB |
| Soundcoat™ (Step) | 89.4 dB |
| Soundcoat™ (Both) | 88.5 dB |
| Concrete Pan | 85.5 dB |

The results showed more variation than the previous test inputs (standardized tapping and hammer drop) and the test repeatability is quite uncertain due to difficulty in replicating footfall locations, shoe contact, and gait of the individual, among other variables. However, for the conditions considered, the stairs with concrete filled pan produced the lowest average peak sound pressures. The Soundcoat™ treated stairs were next with no perceptible difference between the different treatments (~1dB).

## Stairs with Landings

Each of the five sets of stairs that had an accompanying landing (5 different test configurations - all but the concrete-filled pan stairs) were tested with the appropriate matching landing attached. Tests were conducted using the tapping machine and drop tests. Microphones were distributed around the specimen, in accordance with microphone setup II, shown in Appendix 2. The data collection system was identical to that used for prior stair flight tests. The sound pressure levels at third octave bands for each of the five sets of stairs was determined from the recorded sounds.

*Standardized Tapping Test Results*
The standardized tapping machine was placed on the flight of stairs with the landing attached (using the same 4 tapping machine positions shown in Figs. 5a to d). Sound samples were taken at steady state over a period of at least 6 seconds. The sound samples were combined as described previously for the stair flight tests alone in the previous section. The third octave analysis results are shown in Fig. 8. As seen in Fig. 8, the stairs with Soundcoat$^{TM}$ on the step alone or on both the step and riser performed similarly with the lowest sound pressure levels over all the frequency bands. The Line-X$^{TM}$ and Soundcoat$^{TM}$ on the riser alone performed similarly. All the stair treatments produced lower sound pressures than the traditional steel checkered plate stair system. Also comparing Fig. 7 with Fig. 8, the attachment of the stairs to the landing provided only marginal reductions the sound pressure levels compared to the stair flights alone.

The standardized tapping machine was also placed on the landings with the stairs attached (the 4 tapping machine positions are shown in Figs. 6a to d). Sound samples were again taken at steady state over a period of at least 6 seconds and samples were combined as described previously. The third octave analysis results for these tapping machine positions on the landings are shown in Fig. 9. As seen in Fig. 9, for all the Soundcoat$^{TM}$ variants, the stair flight did not affect the landing performance. Further the close response for these three cases indicates excellent repeatability of the tests. The Soundcoat$^{TM}$ treated landing produced the lowest sound pressures over the frequency bands.

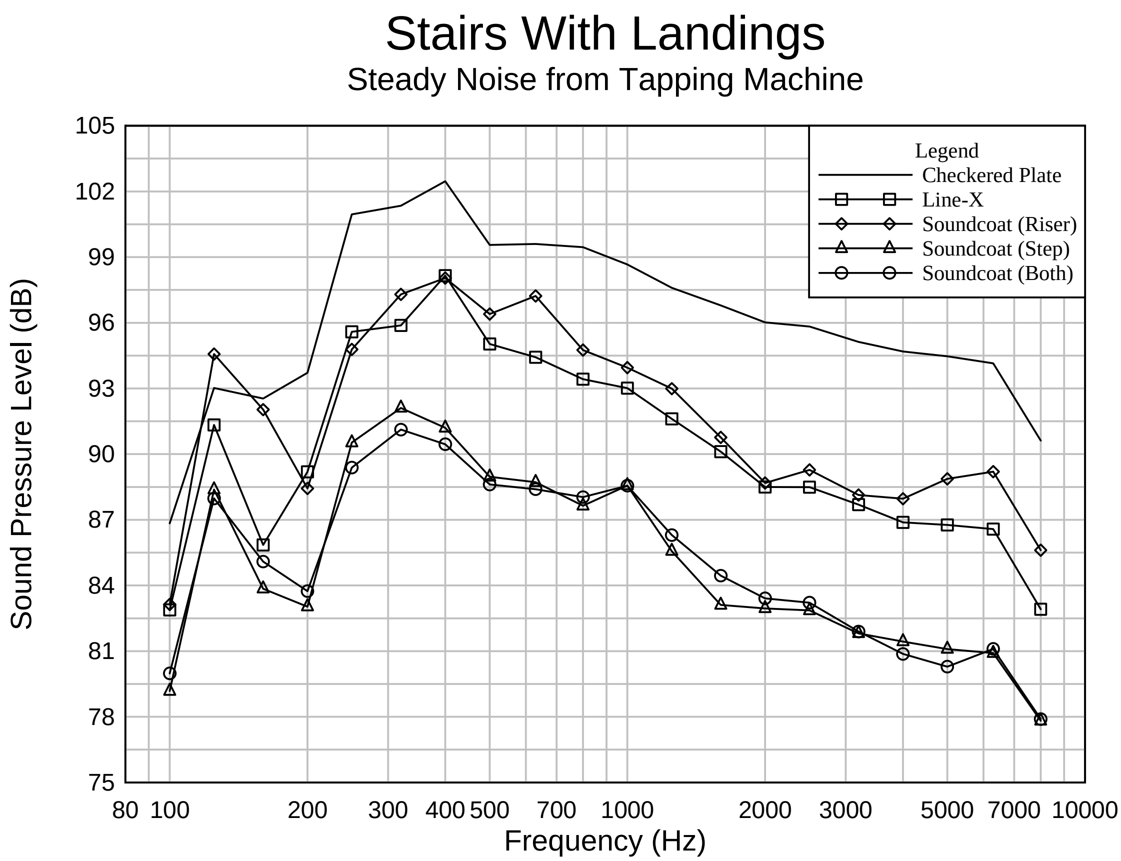



Fig. 8 – Third octave analysis results of standardized tapping tests on stairs connected to landings.

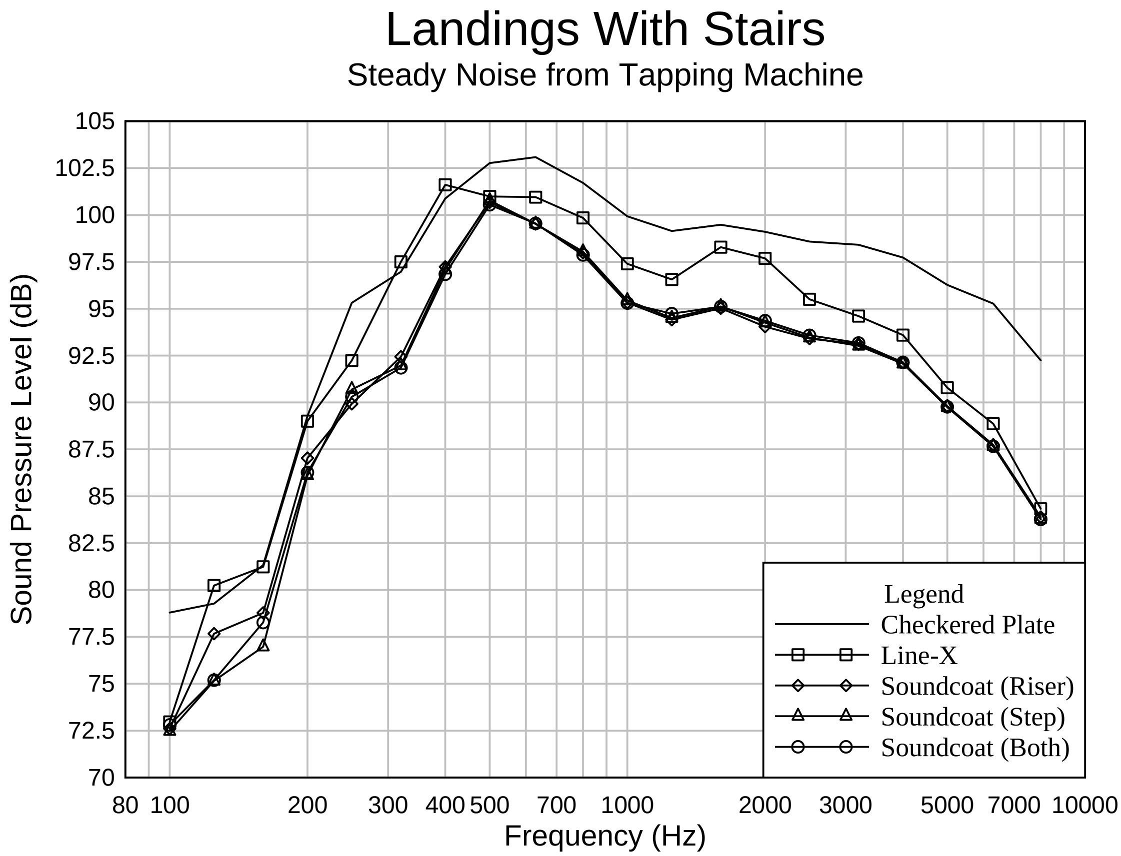



Fig. 9 – Third octave analysis results of standardized tapping tests on landings connected to stairs.

*Drop Test Results*

A 5 lb hammer was dropped from a distance of 1 ft from the surface of the stair tread and the sound pressures were recorded. The drop tests were conducted at the same four stair locations as were used for the tapping machine tests. The instantaneous maximum pressures resulting from each drop and from each microphone were used. From this data (24 sets per stair assembly) the three largest and the three smallest were discarded, the remaining converted to decibels and averaged according to the ISO3741 methods. From these tests, the maximum instantaneous pressures were determined as shown in Table 4. The Soundcoat™ applied to the step and applied to the step and riser performed similarly and provided reduced instantaneous pressures compared to the other systems. The stair performances when subjected to the hammer drops when the landing is attached were similar to those for the stairs alone, although the Soundcoat™ treatments were slightly lower when attached to the landings.

Table 4 – Maximum instantaneous pressures recorded during hammer drop tests on stairs connected to landings.

| Stairs with Landings | |
|---|---|
| Checkered Plate | 124.0 dB |
| Soundcoat™ (Riser) | 121.4 dB |
| Line-X™ | 119.7 dB |
| Soundcoat™ (Step) | 113.0 dB |
| Soundcoat™ (Both) | 112.4 dB |

Similarly, drop tests were performed on the landings when attached to the matching stair. These drop tests were conducted at the same four landing locations as were used for the tapping machine tests. From this data (24 sets per stair assembly) the three largest and the three smallest were discarded, the remaining converted to decibels and averaged according to the methods in ISO3741. From these tests, the maximum instantaneous pressures were determined as shown in Table 5. The Soundcoat™ applied to the step and applied to the step and riser performed similarly and again provided reduced instantaneous pressures compared to the other systems.

Table 5 – Maximum instantaneous pressures recorded during hammer drop tests on landings connected to stairs.

| Landings with Stairs | |
|---|---|
| Checkered Plate | 127.1 dB |
| Line-X™ | 125.3 dB |
| Soundcoat™ (Riser) | 124.0 dB |
| Soundcoat™ (Step) | 120.8 dB |
| Soundcoat™ (Both) | 120.6 dB |

## Conclusions

Relative acoustic performance tests were performed on prefabricated steel stairs and stair/landing assemblies. The stairs were representative of the design, materials, and fabrication used in production. Several different acoustical treatments were applied to the stairs. As no standardized acoustic testing protocols exist for stair assemblies, national and international standards, including ASTM, ISO 140, British and Australian Standards were surveyed and adapted to develop acoustical performance tests of the stairs and stair assemblies. Acoustic testing was performed in the Structural Engineering Research Laboratory at Oregon State University. The stair components and assemblies were placed in a reverberant chamber whose dimensional proportions reasonably represent stairwell applications and correspond to ASTM E492 test room recommendations. Diffusion panels were positioned to enhance the uniformity of the sound within the chamber. To produce sound impacts on the stair components, a standard tapping machine meeting ISO 140 and ASTM E492 was used to produce sound from the stairs. In addition, hammer drop and footfall tests were performed to quantify acoustic performance under representative use. Six microphones meeting accuracy class 1 defined in IEC 61672 were placed throughout the diffuse sound field around the stair assemblies. Microphones, test performance, data collection, analysis and reporting were conducted where applicable to relevant specifications. Based on the test results the following conclusions are presented:

- The traditional steel checkered plate stairs produced the largest sound pressures for almost all frequencies bands and all test conditions.
- The concrete stairs had the lowest sound pressure levels in the low frequency range, although these frequencies are not typically considered as sources of annoyance.
- Over the range of frequencies that the human ear is most sensitive (approximately 1 kHz to 5 kHz) the stairs with Soundcoat™ on the step alone or on both the step and riser produced the lowest sound pressures under tapping conditions. The performance was better than the stair with concrete filled pans over this band of frequencies.
- Annoying sounds are generally associated with higher frequencies and thus the improved acoustic performance of the Soundcoat™ treated stairs in this range of frequencies may be of particular benefit.

- The stairs with Soundcoat™ on the step alone or on both the step and riser also produced the lowest sound pressures for the drop tests. The performance was similar to the stair with concrete filled pans.
- The walking tests provided the most variability in results and the repeatability is uncertain. For these tests, the stairs with concrete filled pans produced the lowest sound pressures. The stairs with Soundcoat™ on the step alone or on both the step and riser produced the lowest pressures of the different alternatives and were approximately 3 dB higher than the concrete filled stair.
- The acoustic performances of the Soundcoat™ treated stairs under all test conditions were about the same whether on the step alone or on both the step and riser.
- Soundcoat™ on the riser alone achieved acoustic performance on par with the Line-X™ coated stair. These were better than the traditional steel checkered plate stair but not as good as the other treatments.
- Application of Soundcoat™ to the step alone would achieve similar acoustic performance (within ~ 1dB) for all test conditions and frequency bands as that when Soundcoat™ is applied to both the riser and step.

## Acknowledgements

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## Appendix 1: Numeric Results

The following table shows the numeric values for the third octave band sound pressure levels for each tapping machine test, in decibels. An initial S indicates stairs alone, an initial L indicates a stair-landing assembly. In the second position, P indicates checkered plate, C concrete, X line-X™, R Soundcoat™ on risers, S Soundcoat™ on steps, and B Soundcoat™ on both. Where there is a third letter, it indicates whether the data is for the stairs (S) or Landing (L) in the stair–landing assembly.

| Frequency | Tapping Machine | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hz | SP | SC | SX | SR | SS | SB | LPS | LSS | LRS | LBS | LXS | LXL | LBL | LRL | LSL | LPL |
| 100 | 88.6 | 70.4 | 85.7 | 86.3 | 82.6 | 83.8 | 86.8 | 79.2 | 83.1 | 80.0 | 82.9 | 73.0 | 72.8 | 72.6 | 72.5 | 78.8 |
| 125 | 93.7 | 67.9 | 91.9 | 94.5 | 87.4 | 87.3 | 93.0 | 88.4 | 94.6 | 88.0 | 91.3 | 80.2 | 75.2 | 77.7 | 75.2 | 79.3 |
| 160 | 89.2 | 72.5 | 86.7 | 91.7 | 84.2 | 84.5 | 92.5 | 83.9 | 92.0 | 85.1 | 85.9 | 81.2 | 78.3 | 78.8 | 77.0 | 81.3 |
| 200 | 93.7 | 77.6 | 89.9 | 87.7 | 83.1 | 85.0 | 93.7 | 83.0 | 88.4 | 83.7 | 89.2 | 89.0 | 86.3 | 87.0 | 86.1 | 89.3 |
| 250 | 102.0 | 82.0 | 97.8 | 96.1 | 91.4 | 89.3 | 101.0 | 90.5 | 94.8 | 89.4 | 95.6 | 92.2 | 90.3 | 89.9 | 90.7 | 95.3 |
| 320 | 100.7 | 87.0 | 96.3 | 97.4 | 92.5 | 91.5 | 101.4 | 92.1 | 97.3 | 91.1 | 95.9 | 97.5 | 91.9 | 92.4 | 92.0 | 97.0 |
| 400 | 102.9 | 88.3 | 99.1 | 98.6 | 91.6 | 90.9 | 102.5 | 91.2 | 98.0 | 90.5 | 98.2 | 101.6 | 96.8 | 97.2 | 97.1 | 100.9 |
| 500 | 99.5 | 86.8 | 95.3 | 96.6 | 89.2 | 88.9 | 99.6 | 89.0 | 96.4 | 88.6 | 95.0 | 101.0 | 100.5 | 100.7 | 100.8 | 102.8 |
| 630 | 99.9 | 90.1 | 94.9 | 97.5 | 89.2 | 88.9 | 99.6 | 88.7 | 97.2 | 88.4 | 94.4 | 100.9 | 99.5 | 99.5 | 99.5 | 103.1 |
| 800 | 99.5 | 88.9 | 93.8 | 95.2 | 87.5 | 88.1 | 99.5 | 87.6 | 94.8 | 88.0 | 93.4 | 99.8 | 97.9 | 98.0 | 98.0 | 101.7 |
| 1000 | 98.6 | 91.5 | 93.5 | 94.2 | 88.6 | 88.6 | 98.7 | 88.6 | 94.0 | 88.6 | 93.0 | 97.4 | 95.3 | 95.3 | 95.4 | 99.9 |
| 1250 | 97.3 | 92.0 | 91.3 | 93.2 | 85.8 | 86.1 | 97.6 | 85.6 | 93.0 | 86.3 | 91.6 | 96.6 | 94.7 | 94.4 | 94.5 | 99.1 |
| 1600 | 96.9 | 92.0 | 89.7 | 90.9 | 83.4 | 84.2 | 96.8 | 83.1 | 90.8 | 84.4 | 90.1 | 98.3 | 95.1 | 95.0 | 95.1 | 99.5 |
| 2000 | 96.1 | 90.1 | 88.3 | 88.9 | 83.1 | 83.2 | 96.0 | 83.0 | 88.7 | 83.4 | 88.5 | 97.7 | 94.4 | 94.0 | 94.3 | 99.1 |
| 2500 | 95.9 | 88.9 | 88.5 | 89.5 | 82.7 | 83.1 | 95.8 | 82.9 | 89.3 | 83.2 | 88.5 | 95.5 | 93.6 | 93.4 | 93.5 | 98.6 |
| 3200 | 95.2 | 87.9 | 87.5 | 88.2 | 81.8 | 81.7 | 95.1 | 81.8 | 88.1 | 81.9 | 87.7 | 94.6 | 93.2 | 93.1 | 93.0 | 98.4 |
| 4000 | 94.8 | 86.3 | 86.4 | 88.0 | 81.4 | 80.6 | 94.7 | 81.4 | 88.0 | 80.9 | 86.9 | 93.6 | 92.1 | 92.1 | 92.1 | 97.7 |
| 5000 | 94.5 | 84.9 | 86.6 | 89.0 | 80.9 | 80.2 | 94.5 | 81.1 | 88.9 | 80.3 | 86.8 | 90.8 | 89.8 | 89.8 | 89.7 | 96.3 |
| 6300 | 93.8 | 83.7 | 86.5 | 89.1 | 80.6 | 80.7 | 94.1 | 80.9 | 89.2 | 81.1 | 86.6 | 88.9 | 87.7 | 87.7 | 87.7 | 95.3 |
| 8000 | 90.1 | 80.7 | 82.7 | 85.5 | 77.3 | 77.3 | 90.6 | 77.8 | 85.6 | 77.9 | 82.9 | 84.3 | 83.8 | 83.9 | 83.8 | 92.2 |

The following table shows the numeric values for the third octave band sound pressure levels for each of the decay and background noise tests, in decibels.

| Frequency | Background | | Decay | |
|---|---|---|---|---|
| Hz | Water | No Water | Alpha | RT60dB |
| 100 | 41.8 | 39.8 | 0.123 | 0.69 |
| 125 | 40.8 | 39.7 | 0.109 | 0.78 |
| 160 | 39.4 | 38.7 | 0.120 | 0.70 |
| 200 | 38.9 | 37.3 | 0.107 | 0.79 |
| 250 | 38.3 | 36.2 | 0.083 | 1.01 |
| 320 | 37.2 | 35.9 | 0.069 | 1.23 |
| 400 | 37.6 | 37.2 | 0.052 | 1.63 |
| 500 | 38.6 | 40.4 | 0.040 | 2.10 |
| 630 | 39.6 | 41.5 | 0.038 | 2.20 |
| 800 | 40.4 | 41.5 | 0.037 | 2.25 |
| 1000 | 43.2 | 43.6 | 0.045 | 1.87 |
| 1250 | 42.1 | 44.1 | 0.051 | 1.66 |
| 1600 | 44.3 | 45.0 | 0.053 | 1.59 |
| 2000 | 45.0 | 46.5 | 0.054 | 1.57 |
| 2500 | 46.5 | 47.6 | 0.053 | 1.60 |
| 3200 | 46.2 | 48.4 | 0.056 | 1.51 |
| 4000 | 47.6 | 50.0 | 0.059 | 1.44 |
| 5000 | 48.4 | 50.7 | 0.059 | 1.43 |
| 6300 | 49.8 | 51.5 | 0.062 | 1.37 |
| 8000 | 50.4 | 54.3 | 0.067 | 1.27 |

## Appendix 2: Microphone, Speaker and Tapping machine locations

The following tables indicate the locations and orientations of the microphones and location of the speaker during the calibrations, then the locations and orientations or the microphones during testing. The coordinate system is defined with the front, right, and top represented by the positive x y and z directions, with the origin in the back left bottom corner. Orientation notation indicates the angle backward or forward, then left or right, then up or down, when viewed from the front of the box. During the testing, all of the microphones were oriented towards the specimen.

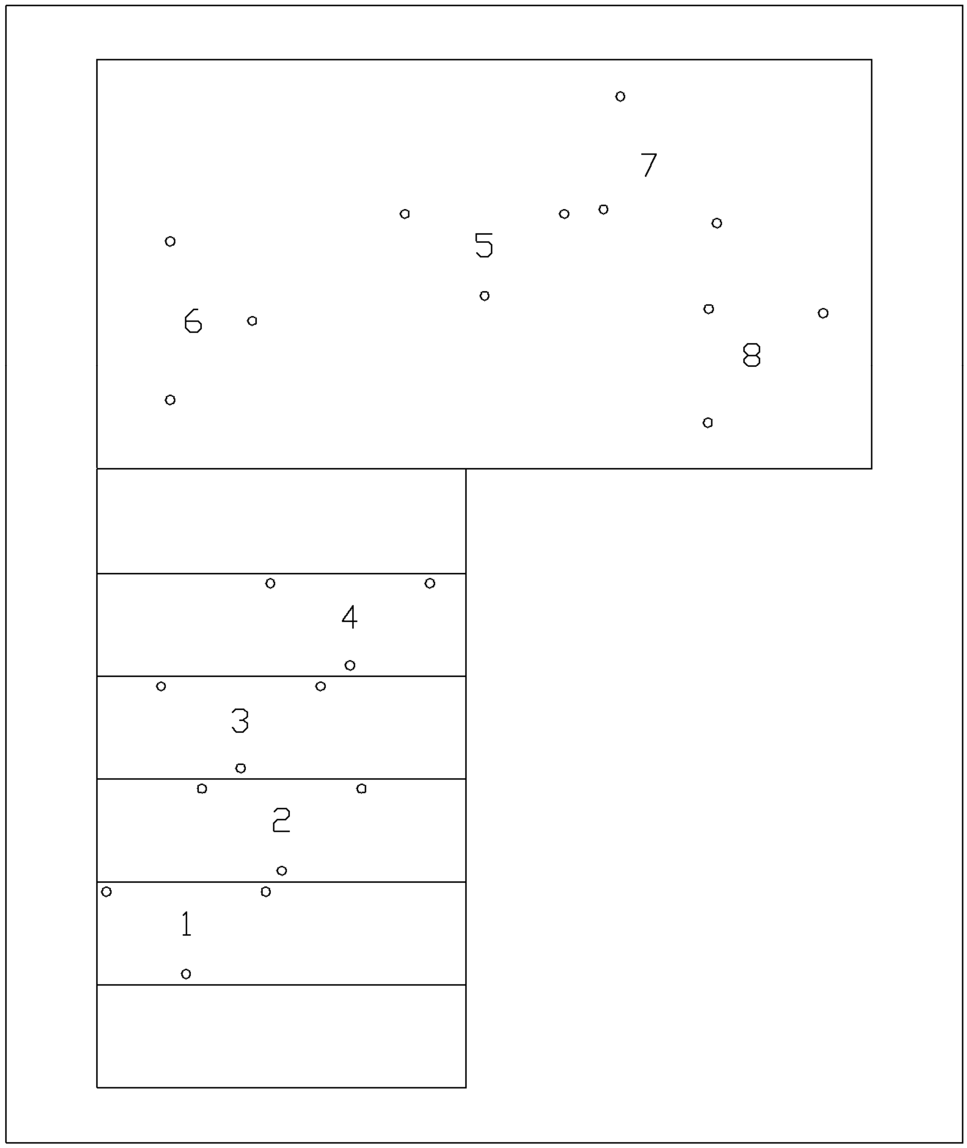
Microphone and Speaker Setup #1: Calibrations

| | Position | | | Orientation | | |
|---|---|---|---|---|---|---|
| Microphone | x | y | z | x | y | z |
| Orange 1 | 34.5 | 41.5 | 109.5 | 25B | 65L | 65U |
| Orange 2 | 35.5 | 86 | 36.5 | 45B | 45L | 0 |
| Orange 3 | 93 | 68.5 | 52 | 35F | 55L | 20U |
| Orange 4 | 38 | 41 | 29 | 20F | 70R | 10D |
| Orange 5 | 99 | 20 | 63 | 20B | 70R | 30U |
| Orange 6 | 69 | 71.5 | 92 | 85F | 5L | 35U |
| Speaker 1 | 52.5 | 28 | 0 | - | - | - |
| Speaker 2 | 95 | 41.5 | 0 | - | - | - |
| Speaker 3 | 63 | 94.5 | 0 | - | - | - |

Microphone Setup #2: Testing

| | Position | | | Orientation | | |
|---|---|---|---|---|---|---|
| Microphone | x | y | z | x | y | z |
| Orange 1 | 34.5 | 39 | 107.5 | 85B | 5L | 70D |
| Orange 2 | 103.5 | 71 | 37 | 10B | 80L | 25D |
| Orange 3 | 51 | 64.5 | 22.5 | 40F | 50L | 10U |
| Orange 4 | 42.5 | 29 | 26 | 85B | 5R | 30U |
| Orange 5 | 69 | 80 | 62 | 5B | 85L | 30D |
| Orange 6 | 70 | 80 | 91.5 | 10B | 80L | 60D |

The following schematic shows the eight approximate locations of the tapping machine on the stairs during testing:


7
5
6
8
4
3
2
1

**Appendix 3: Testing Conditions**

| | |
|---|---|
| Manufacturer: | Pacific Stair |
| Client: | Pacific Stair |
| Test specimen installed by: | Oregon State University Civil Engineering |
| Test room: | OSU Reverberation Chamber |

Testing conditions for the calibrating tests were as follows. The fundamental frequencies were determined on Aug. 11, after the water running background sample was taken.

| Test | Date | Humidity | Temp. |
|---|---|---|---|
| Background: Water Running | Aug. 11 | 58% | 28° C |
| Background: None | Aug. 16 | 51% | 27° C |
| Decays | Aug. 17 | 46% | 27° C |

Testing conditions for the stairs were as follows:

| Setup | Date | Humidity | Temp. | Shims | Background Noise |
|---|---|---|---|---|---|
| LP | Aug. 19 | 42% | 28° C | 0 | Tapping, Dropping: None<br>Walking: Water Running |
| LB | Aug. 20 | 53% | 28° C | 2 | None |
| LS | Aug. 20 | 55% | 28° C | 2 | Water Running |
| LR | Aug. 20 | 59% | 28° C | 0 | Tapping: None<br>Walking, Dropping: Water Running |
| LX | Aug. 22 | 64% | 25° C | 0 | Water Running |
| SX | Aug. 22 | 62% | 25° C | 0 | Tapping: None<br>Walking, Dropping: Water Running |
| SC | Aug. 22 | 60% | 26° C | 1 | None |
| SB | Aug. 22 | 58% | 27° C | 2 | Water during tapping<br>No noise for the rest |
| SR | Aug. 22 | 55% | 27° C | 0 | No Noise |
| SS | Aug. 22 | 52% | 28° C | 2 | Walking: Water Running<br>Tapping, Dropping: None |
| SP | Aug. 22 | 49% | 29° C | 2 | None |

## Appendix 4: Example microphone calibration

BSWA TECH

**Calibration Chart**

**Model: MPA 201 Serial No: 450895**

MP201 Serial No: 460593 MA211 Serial No: 470056

**MPA201 Sensitivity :**

-27.4 dB ref 1 V/Pa or 42.7 mV/Pa @ 250Hz

Signature: Date: 06/18/2009

**Test Conditions:**

| | |
|---|---|
| Polarization Voltage : | 0 V |
| Barometric Pressure : | 101.3 kPa |
| Relative Humidity: | 30% |
| Temperature: | 20 ℃ |

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