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Case study: Mitigation of excessive vibration induced by commercial washers on elevated post-tensioned concrete slab

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ABSTRACT

During renovation of a luxury hotel, installation of commercial grade washer/extractors on an elevated post-tensioned concrete slab resulted in excessive vibrations of the floor slab during the extraction cycle. Vibration was measured and the operational characteristics of the washer/extractors were analyzed to evaluate potential vibration isolation options. Tight structural constraints limited options for potential vibration isolation and structural stiffening. Additionally, a tight construction schedule dictated by the hotel provided only five weeks for observation, analysis, and design and implementation of mitigation to allow for on-time opening and operation of the facility.

1. INTRODUCTION

Noise and vibration from rotating laundry equipment found in hotels is a potential source of complaints from occupants when not properly isolated. Specialty equipment, such as commercial washer/extractors, requires additional attention to avoid transmitting excessive noise and vibration into the building structure, especially when installed above grade. Excessive vibration can be disruptive to building occupants, in addition to potentially fatiguing the building structure itself.

While internal isolation options are offered by washer/extractor manufacturers to reduce such transmission, they do not always provide adequate efficiency for all operating cycles when the equipment is not installed on a slab-on-grade floor. Such equipment can be addressed during the design phase of new projects; however, options can be limited when dealing with existing building renovation projects, especially under tight time constraints.

This paper describes a case study in which a luxury hotel installed high capacity commercial washer/extractors on an elevated post-tensioned concrete slab. After the initial operation resulted in excessive floor vibration in the laundry services room that concerned hotel staff, the hotel ceased all onsite laundry operations. The hotel owner demanded an immediate solution be implemented to restore onsite laundry facilities to full capacity prior to the hotel's opening, which was five weeks away.

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2. VIBRATION CRITERIA

Vibration can be assessed with respect to human response to vibration and for potential damage to sensitive equipment in a building[1]. ASHRAE summarizes acceptable vibration criteria in a building structure. From Figure 1 below, an RMS velocity of 0.032 in/s (32,000 µin/s) is recommended as a maximum for vibration levels measured in "workshops".

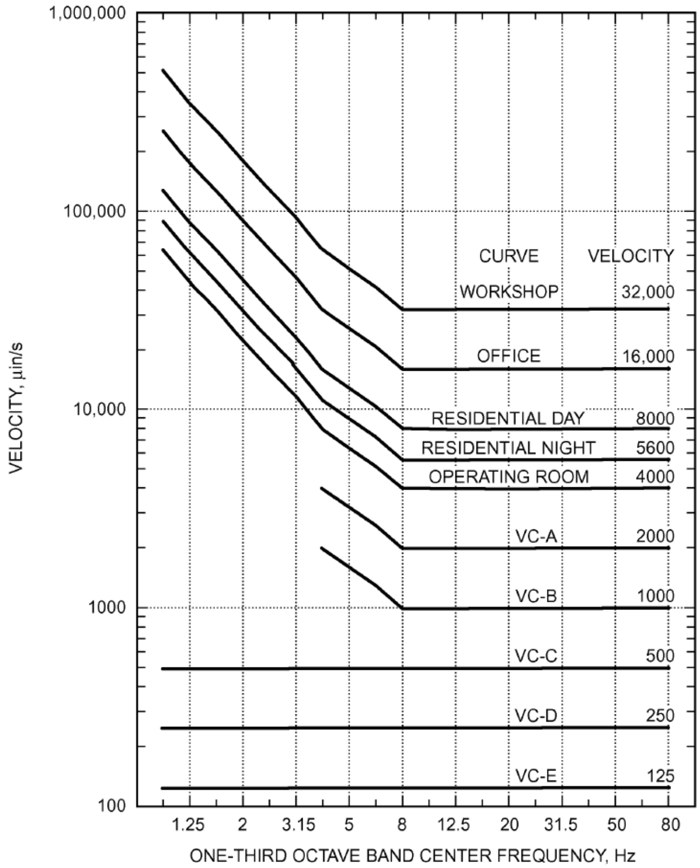

Figure 1: ASHRAE suggested vibration criteria for occupied buildings[2].

While the ASHRAE criteria is not required by the International Building Code (IBC) or stipulated in any Colorado or City of Denver code or ordinance, it is used as an industry standard for gauging acceptable levels of vibration susceptible to human perception.

The primary criteria used in this study are the human response to vibration, and the maximum "workshop" criteria suggested by ASHRAE.

3. COMMERCIAL WASHER/EXTRACTOR UNITS

A. Rigid Machines

Rigid or "solid mount" washer/extractors do not incorporate any type of internal isolation and are mounted directly to a floor slab or supporting structure. Due to the lack of internal isolation, the supporting structure must be designed to sustain greater dynamic forces (than those resulting from flexibly-mounted machines). As such, rigid washer/extractors are typically mounted on grade. While rigid machines can be installed above grade, they require additional stiffening in the supporting structure to handle the increased dynamic forces.

B. Flexibly-Mounted Machines

Flexibly-mounted ("suspended" or "soft mount") washer/extractor machines incorporate internal isolation, typically via a combination of springs and shock absorbers, to reduce vibration transmitted to the floor or supporting structure. This allows for higher extraction speeds while transmitting less vibration to the supporting structure. However, care must still be taken to provide sufficient rigidity at the supporting structure when using flexibly-mounted machines in above grade installations.

4. VIBRATION ISOLATION

A. Vibration Isolation for Rotating Equipment

Vibration from rotating equipment can easily transmit from one space to an adjacent space, and to distant floors in multi-story buildings. In general, it is necessary to vibration isolate washer/extractors, chillers, pumps, air-handlers, generators, etc., from the building structure to reduce vibration transmitted to the supporting floor slab, and potentially other areas of the building. Vibration isolators are selected for a specific piece of equipment based on its operating characteristics, location within the building, and the design of the structural supporting system. Washer/extractors are more problematic than most pumps, fans, etc., due to large unbalanced forces and relatively slow speeds. Vibration isolators can vary greatly in design, shape and size, such as thin rubber pads, steel spring and air spring isolators.

Where the building structure does not provide sufficient rigidity to adequately support rotating equipment, as is the case with longer floor spans, additional structural stiffening is required. Movement of flexible floors supporting vibration isolated rotating equipment decreases isolator efficiency and results in increased vibration transmission. In the extreme, resonances can develop with vibration isolated equipment and the flexible floor structure which can result in excessive motion of the isolated equipment, the floor, and potential failure of the floor structure itself.

B. Inertia Bases

Vibrating and rotating equipment with large unbalanced forces, high centers of gravity, or large start-up transients, often require inertia bases to control the displacement of the equipment when mounted on soft springs. An inertia base typically weighs far more than the equipment it supports, and often consists of reinforced concrete.

The weight of the inertia base stabilizes the motion of the equipment it supports by allowing a stiffer spring to be used[3]. Stiffer springs result in smaller displacements for a given force, while still providing acceptable vibration isolation. The result is that the equipment and the inertia base move less when subjected to dynamic forces.

The ultimate thickness and weight of an inertia base is dependent upon the total weight of the equipment being supported and the magnitude of the dynamic forces. Inertia bases are vibration isolated from the supporting building structure with isolation mounts, selected specifically for the characteristics of the base/machine assembly. Isolation mounts for the complete inertia base/machine assembly are ideally secured to the structure at locations of maximum mass and rigidity. Clearances around and below the inertia base should be accounted for during design and provided during installation to allow for the expected motion.

C. Flexible Connections

While spring isolators and inertia bases significantly reduce vibration transmitted from rotating equipment to building structures, vibration can also be transmitted though piping that is rigidly attached to the equipment. As such, flexible connections should be implemented at all electrical conduit and piping-to-equipment connections.

5. CASE STUDY: LUXURY HOTEL WITH EXCESSIVE VIBRATION WITHIN LAUNDRY SERVICE ROOM

A. Observation

The renovation of a building to create a luxury hotel included the addition of commercial washer/extractors. Upon operation of the commercial washer, excessive vibration was immediately perceptible in the elevated post-tensioned concrete floor-slab by laundry facility personnel when the washers accelerated to their full extraction speed. The hotel owner demanded a solution be implemented to restore onsite laundry operations to full capacity prior to the hotel's opening, five weeks away.

The laundry equipment consisted of a bank of three "soft mount" 170 lb. capacity Pellerin/Milnor #42032X7J washer/extractors, and one "soft mount" 60 lb. capacity Pellerin/Milnor #30022X8J washer/extractor. The washer/extractors were rigidly fastened to the elevated 9" thick post-tensioned flat plate concrete floor slab of the building's 3rd sublevel, which spanned 30 ft. between columns. A photo of the installed washer/extractors is shown in Figure 2.

Prior to the building renovation, the laundry services room had been a parking garage, whereby the original intent of the structure was for use as a parking garage. Parking spaces were still in use in areas around the washer/extractors, and on the two levels below (the lowest of which is slab-on-grade).

Figure 2: 170 lb. capacity washer/extractors as initially installed.

In this specific case, a unique approach to mitigating vibration from the washer/extractors was required due to structural limitations, time constraints, and lack of desire to further alter the hotel's recently renovated areas.

B. Analysis

To determine the problem frequency and velocity of vibrations on the floor slab, measurements were performed in the laundry facility space when floor vibration was subjectively most pronounced. This occurred when the washer/extractors began accelerating into their extraction cycle.

A laptop based LDS-Dactron Photon II portable dynamic signal analyzer was used with a PCB Piezotronics Model 393 B31 ICP® accelerometer (635 grams) to measure acceleration on the floor slab. From the acceleration measurements, velocity and displacement values could be determined. The accelerometer was fastened to the bare concrete floor with a small amount of wax. The accelerometer location is shown by Figure 3.

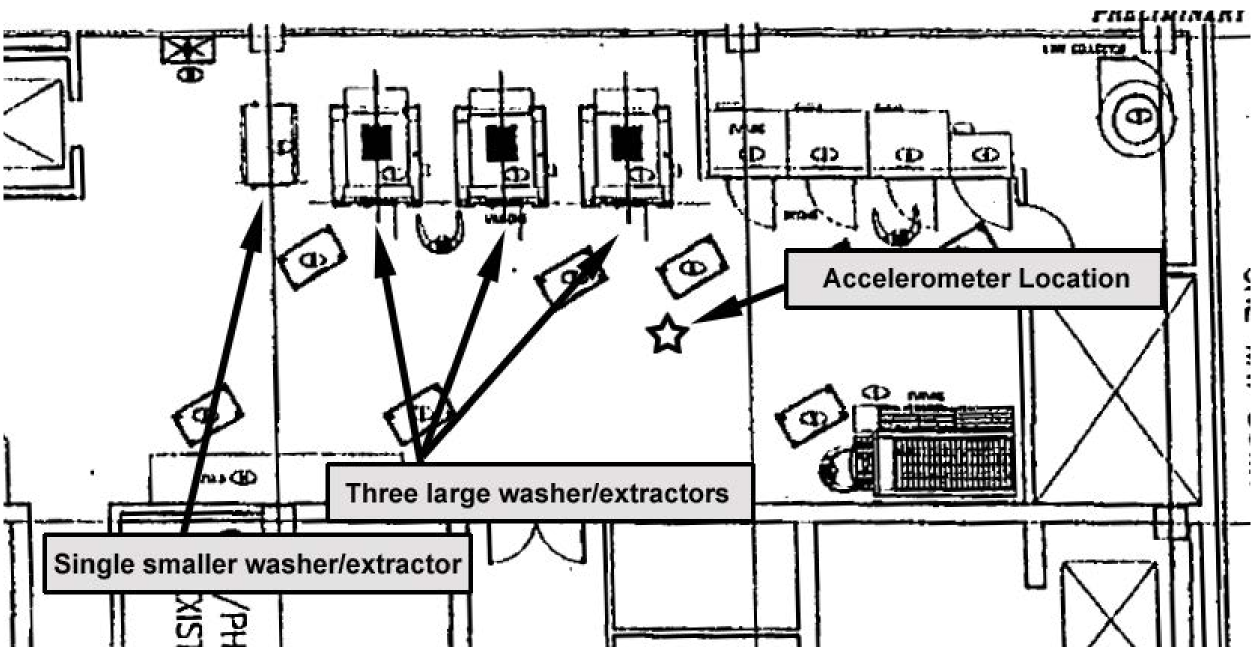

Figure 3: Floor plan of laundry services space.

Known unbalanced loads were induced in the washer/extractors to excite the floor slab and to measure vertical vibration in the floor slab. This was done by taping dry bath towels together to create a single 10 pound load and 20 pound load. The machine manufacturer felt that the worst case unbalanced load would be in this weight range. The load was placed into the washer/extractor, and the washer/extractor was set into its extraction cycle (without water). Vibration was measured while the equipment ramped up into extraction, and once it reached its steady extraction RPM. To achieve a full extraction speed of 12.5 Hz (750 RPM), the machines slowly ramp up over a period of approximately 3 minutes.

Vertical vibration from these unbalanced loads in a single washer/extractor was measured and found to be far above industry standard criteria for a “workshop” of 0.032 in/s. The data is plotted in one-third octave bands in Figures 4, 5, and 6.

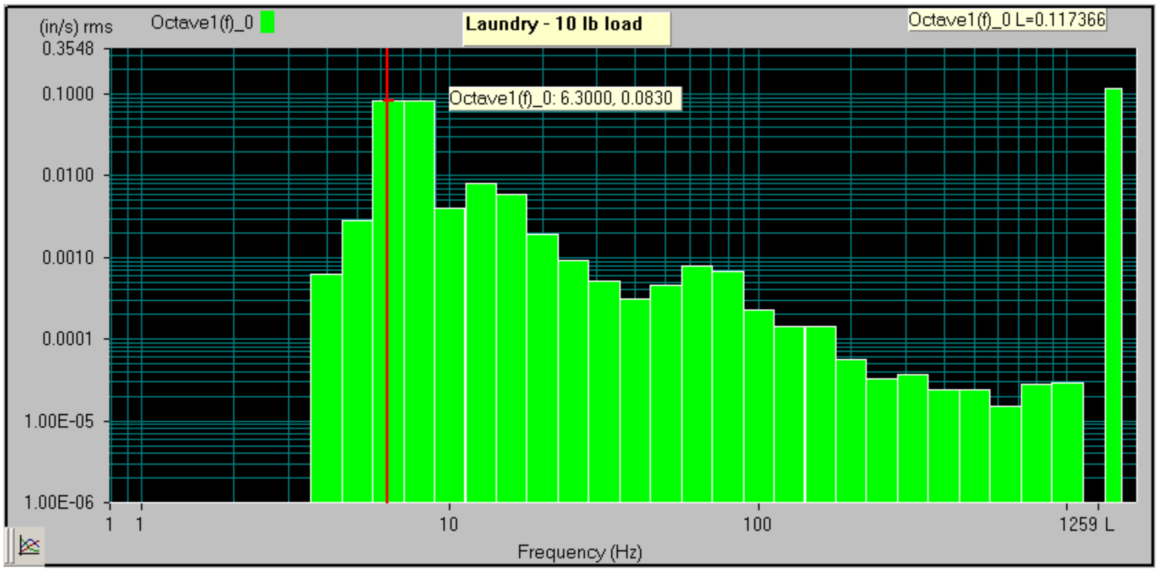

Figure 4: Vertical vibration with 10 lb. unbalanced load while accelerating to extraction RPM - 0.083 in/sec at 6.3 Hz and 8Hz, almost 3 times criteria.

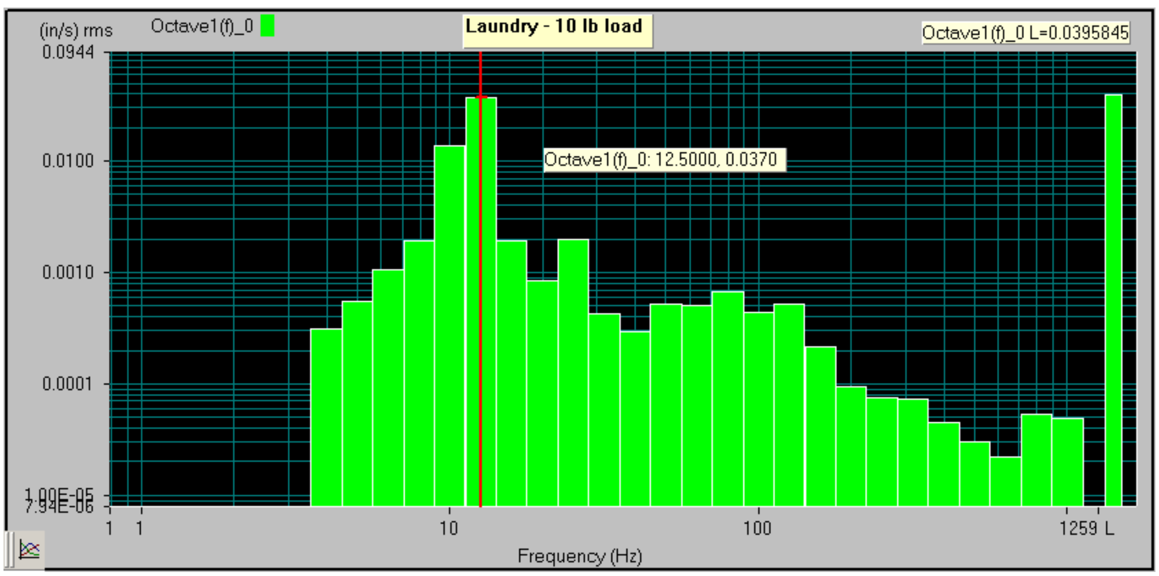

Figure 5: Vertical vibration with 10 lb. unbalanced load during steady extraction RPM - 0.037 in/sec at 12.5 Hz, slightly above criteria.

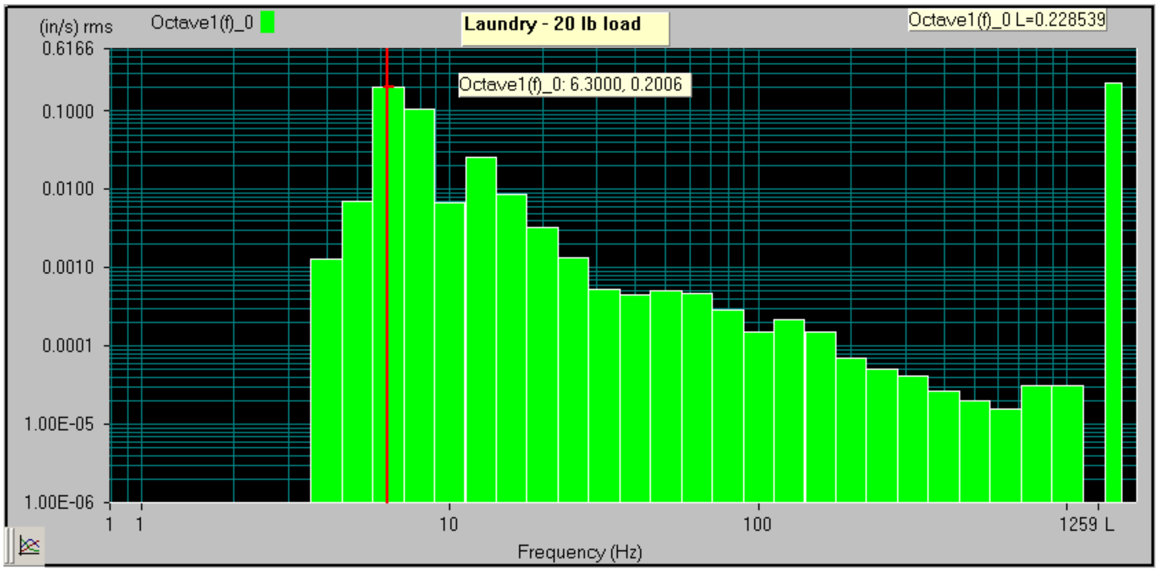

Figure 6: Vertical vibration with 20 lb. unbalanced load while accelerating to extraction RPM - 0.201 in/sec at 6.3 Hz.

In Figure 4, you can see that the vibration velocity levels are almost three times the criteria of 0.032 in/s in the 6.3 Hz and 8 Hz bands, with a 10 pound unbalanced load. Figure 5 shows the data when the machine reached full speed in the extraction cycle. The vibration was much less severe at this speed, and marginally acceptable. Figure 6 shows the vibration levels with an unbalanced load of 20 pounds, which as expected, is approximately twice as severe as with the 10 pound load unbalance. Even though the dynamic force is higher at higher speeds, the vibration levels were highest when the extraction speed passed through the 6.3 Hz one-third octave band, which indicated a resonance condition.

To understand the interaction of the washer/extractors with the supporting structure, it was necessary to determine the natural frequency of the 9” thick post-tensioned concrete floor slab. This was done by exciting the floor slab with a heel drop, and measuring the resulting vibration. Heel drop tests simply involve a person standing with their heels several inches above the floor, and dropping their weight simultaneously onto their two heels. The results of the heel drop test showing a natural frequency of approximately 6.5 Hz are shown in Figure 7.

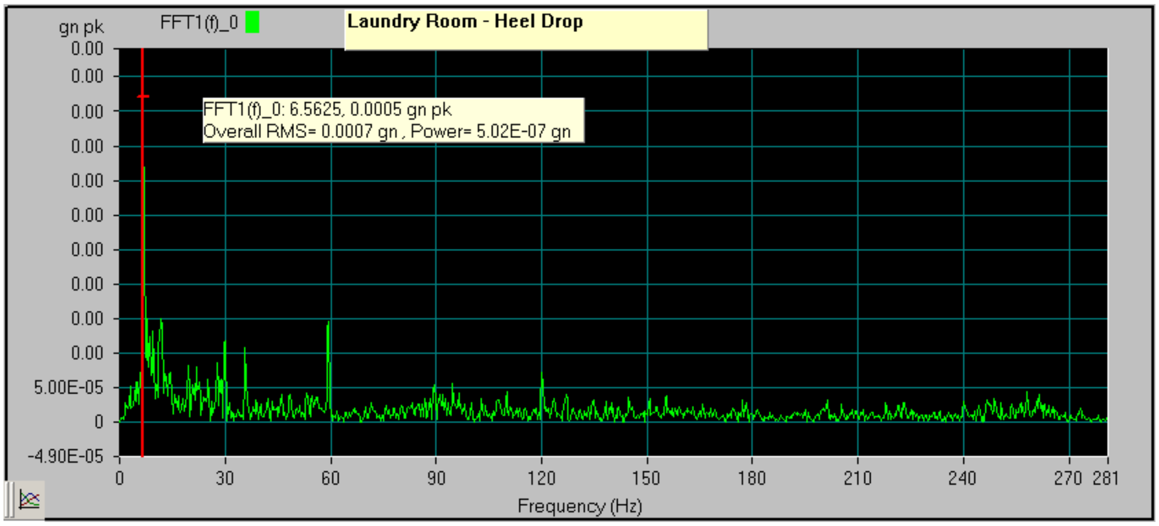

Figure 7: Heel drop test – natural frequency (Fn) of laundry floor slab = 6.56 Hz.

Results from the vertical vibration measurements determined that vibration was most severe at 6.3 Hz and 8 Hz with 10 pound and 20 pound loads, respectively, while the washer/extractors were accelerating to their full extraction speed. To achieve a full extraction speed of 12.5 Hz (750 RPM), the machines slowly ramp up over a period of approximately 3 minutes. It is during this ramp up period that the operating frequency (or forcing frequency) of the washer/extractors, matched the natural frequency of the floor, for a period of about 10 to 20 seconds, causing a resonance in the floor slab, and the resulting excessive vibration.

C. Recommendations

To reduce vibration from the washer/extractors, a variety of options were presented to the design team. Initially, it was thought that stiffening the structure by implementing a steel truss or concrete column system to grade would be the easiest solution. However, it was discovered that the PT floor slab was not designed to sustain additional support at mid-span and could result in potential failure of the slab. Additionally, the loss of the rental parking spaces on the two sub-levels required to provide such support was unacceptable to the hotel owner. The real estate limitations imposed also prohibited relocation of the laundry facilities to a slab-on-grade level. With options limited to the existing laundry location, the possibility of completely replacing the washer/extractors with smaller units was explored. However, it was considered economically prohibitive by the hotel owner, and would have been a difficult undertaking since the units were “built in” to the laundry room. Additionally, the cost and labor of rerouting supply/waste piping to new machines was also considered as an undesirable expense.

Adding damping to the laundry floor slab to reduce the vibration levels at resonance was also considered. Since adding damping above the floor slab was impractical, damping would most likely have to be in the form of a tuned mass damper on the underside of the floor. Since the vibration levels at the non-resonant frequencies were marginal and may not have been acceptable even in absence of the resonant condition, the addition of damping was not pursued further as a solution.

With the understanding that the existing machines and location must be used, modifications to the machines themselves were considered. Since the "soft mount" machines incorporated internal isolators, "locking down" or replacing the built-in isolators and providing more efficient floor-mounted isolators was evaluated. However, this option was not approved by the machine manufacturer, and would have voided the washer/extractor's warranty.

Since the machines must be used in an unmodified condition, isolating the machines on inertia base was the only available option. A common base was selected over individual bases to increase stability. It was determined that an 8" thick inertia base weighing approximately 45,000 pounds would be required to adequately support the machines and isolate vibration from the washer/extractors. However, the load capacity of the laundry floor slab did not allow for a machine/inertia base assembly of that size to be supported mid-span. While it was determined that an inertia base could be adequately supported at the rear of the machines very close to the structural columns, it was impossible to support the front of the inertia base from the floor. The idea of suspending the inertia base from the floor-slab above was proposed.

The slab at the First Floor of the hotel was found to be stiffer than that at the laundry, and had higher capacity to carry additional load. However, the occupancies on the floor above were more sensitive to vibration than the laundry area. Heel drop tests were performed on the floor slab at the floor above the laundry, and its natural frequency was found to be approximately 14 Hz, which was close to, but above, the operating range of the washer/extractors. The results of the heel drop test performed at the First Floor are shown in Figure 8. If a resonant condition was experienced, the manufacturer indicated that it was possible to slow the top extraction speed of the machine slightly.

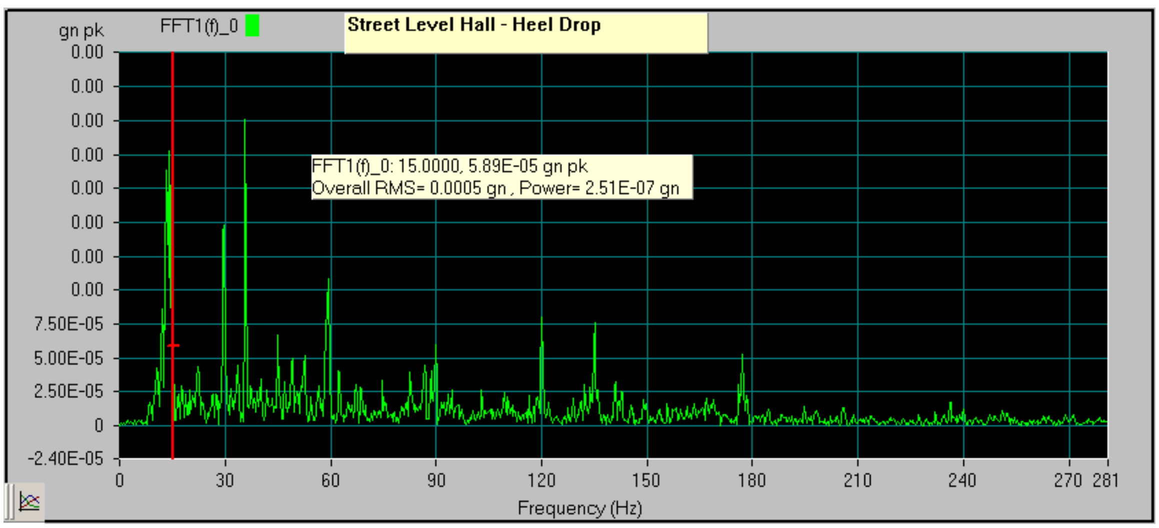

Figure 8: Heel drop test – natural frequency (Fn) of First Floor slab = 14 Hz.

It was decided to mount the rear of the inertia base on the floor of the laundry room near the structural columns, and the front of the inertia base would be suspended from the First Floor slab above. While this required removal of the existing lay-in ceiling system to install spring hangers, most of the electrical and supply/waste piping for the washer/extractors could remain in place. Figures 9, 10, and 11, depict progress of the inertia base installation.

Figure 9: Isolation hanger at front of inertia base.

Figure 10: Spring isolator at rear of base at column.

Figure 11: Inertia base during installation.

D. Results

While vibration could not be measured after installation of the inertia base was complete, vibration was subjectively difficult to detect. Moreover, the owner was satisfied with the results, as the hotel was able to commence with onsite laundry operation, and meet their grand opening date.

Some minor modifications were required after the initial installation. The required clearance around the inertia base was not provided and there was contact between parts of the inertia base and the floor. This was remedied by chiseling the floor in small areas. Approximately ½" of movement (peak-to-peak) was expected at the natural frequency of the spring isolators, and this was very close to the movement experienced as the extractor began to ramp up its speed. Another issue was the lateral movement of the inertia base. The machines transmit horizontal forces as well as vertical forces. This was anticipated, but a decision was made to take a "wait and see" approach to determine how significant the movement due to these loads was. The floor mounted springs were able to resist the horizontal loads with minimum lateral movement, but the front of the inertia base that was suspended tended to sway. The movement in itself, up to ½", was not a problem. However, the lateral movement caused an internal limit switch on the washer/extractors to trip occasionally. To limit this movement, snubbers were installed on the floor, at the two ends of the base, to restrict the lateral movement of the base. Installed snubber, which consisted of neoprene waffle pads and steel angle, is shown in Figure 12.

Figure 12: Snubber installed at end of inertia base to restrict lateral movement.

The final installation of the washer/extractors on the inertia base is shown in Figure 13.

Figure 13: Washer/extractors on retrofitted inertia base.

6. SUMMARY AND CONCLUSIONS

Rotating equipment is often installed in hotels without consideration of noise and vibration. This paper details a case study in which a hotel owner was forced to implement very significant measures to adequately isolate washer/extractors from transmitting vibration to an elevated concrete floor slab after completion of a building renovation project. Had the laundry space vibration been addressed during design, then the installation cost would have been much less; it may have even possible to relocate the laundry space to a slab-on-grade location, or consider different washer/extractor units altogether.

REFERENCES

[1] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. "SOUND AND VIBRATION CONTROL," Chap. 47 in *2007 ASHRAE Handbook: HVAC APPLICATIONS*, (ASHRAE, Atlanta, Georgia, 2007).

[2] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. "SOUND AND VIBRATION CONTROL," Chap. 47, Figure 37, in *2007 ASHRAE Handbook: HVAC APPLICATIONS*, (ASHRAE, Atlanta, Georgia, 2007).

[3] William J. Cavanaugh and Joseph Wilkes, "Building Noise Control Applications," Chap. 3 in *Architectural Acoustics, Principles and Practice,* edited by William J. Cavanaugh and Joseph A. Wilkes, (Wiley, New York, 1999).