Groundborne Noise and Vibration Control at Performing Arts Centres Using Elastomeric Bearings

Steven L. Wolfe

Wilson, Ihrig & Associates, Inc., Emeryville, California, USA

ABSTRACT

A major challenge for new performing arts centers in major cities is to achieve sufficiently low levels of background noise. Thus there is the need to isolate the new structures from vibration sources typically found in urban downtown areas. This paper provides background information, typical design details and procedures used to ensure that the groundborne noise and vibration from outside activities will be inaudible or sufficiently low inside performing arts venues. Specific design procedures are presented with respect to the Four Seasons Centre for the Performing Arts, Canada's first purpose-built opera house located in Toronto. Results of follow-up measurements are presented which confirmed that the vibration design effectively mitigated the outside vibration and noise intrusion inside the auditorium to achieve background noise levels from exterior sources equivalent to the threshold of human hearing.

INTRODUCTION

There has always been the desire to design new performing arts centres with state of the art acoustics. Within the last 20 to 25 years state of the art acoustics also means sufficiently low background noise such that both exterior airborne and particularly groundborne noise are inaudible or only occasionally audible. With the desire to locate these performance venues in downtown areas, close to public transportation and other cultural institutions, the need for vibration isolation of the hall must be considered in order to achieve appropriate ambient background noise levels.

Specifically, provision of structural vibration isolation of either the entire building or of the performance hall(s) within the building, creating a box-in-box type of structure, has proved to be a design that can achieve acceptability at these noise and vibration impacted sites.

Typical sources requiring vibration isolation include freight railroads within approximately 250 to 300 m; passenger rail lines (subway or surface) within approximately 50 to 120 m; roads (particularly tunnels) with a high volume of trucks or buses within approximately 40 m; nearby mechanical equipment such as pumping stations, tunnel vent fan structures or central plant facilities; nearby rivers or shipping channels with diesel powered boats or ships and other noisy spaces within multipurpose buildings.

A number of different materials can be and have been used for vibration isolation with various degrees of success. Materials used have included lead-asbestos pads; steel springs; load-bearing fibreglass pads; a heavy foundation with a thick concrete slab and elastomeric bearings. Elastomeric bearings have included neoprene, natural rubber, synthetic rubber, polyurethane and polystyrene foam.

We have found that natural rubber provides favourable characteristics for building isolation. These characteristics include a low ratio of dynamic to static stiffness, very low creep rate under compressive load and a very long service life without deterioration or stiffening.

In this paper, the general design approach will be discussed along with a case study indicating specific vibration isolation design aspects of the Four Seasons Centre for the Performing Arts, Canada's first purpose-built opera house located in Toronto next to a rail transit subway tunnel, a surface streetcar line and streets with significant bus and truck traffic.

GENERAL DESIGN APPROACH

Site Assessment

Groundborne noise and vibration can be estimated from local soils studies and general information regarding the source of groundborne noise and information on the proposed facility structural design. However, the preferred and most accurate procedure for evaluation of groundborne vibration at the site is a measurement survey supplemented by measurements in boreholes with depth equivalent to the proposed building foundation level. Measurements can also be made in existing nearby buildings, but considerations must be made for differences between the existing building and new facility in terms of type of foundation and structure. If airborne noise measurements are made in nearby buildings to characterize groundborne noise (primarily applicable to sub-surface sources), additional corrections must be made in terms of the size and nature of the existing space in comparison with the performance space.

The maximum levels from the groundborne vibration measurements are analysed in terms of 1/3 octave band RMS levels and define the structure-borne vibration that will be transmitted into the foundation of the new structure. These data are then used to project the levels of structure-borne noise expected to be transmitted through the building structure and re-radiated from the floors and walls of the performance spaces.

Prediction and Evaluation of Expected Noise Levels

Predicting the expected noise levels includes estimating the coupling loss of the vibration transmitted into the foundation or base levels of the building structure. For a heavy reinforced concrete structure, a coupling loss of 10 to 15 dB can be expected when founded on competent soils without solid rock, while for a relatively lightweight steel frame building, with composite concrete floor, the coupling loss may only be 5 dB. Next the transmission through the building must be considered. For a heavy concrete building, there may be little transmission loss through the building while a steel frame building will typically provide 1 to 3 dB attenuation per floor. There are certainly exceptions to these values for coupling loss and transmission through the building, but are provided to give a general estimate of what can be expected to assist in the prediction of expected noise levels. Once in the building, the vibration excites the floor, walls and ceiling to generate structure-borne noise which radiates into the performance space. Typically, these vibration levels which excite the interior room surfaces are below the level of feelability, but can still radiate significant noise levels within the performance space in the frequency range of approximately 20 Hz to 500 Hz. The interior noise levels are then calculated by converting the 1/3 octave band levels to octave band levels and estimating the sound absorption within the interior spaces and the radiation efficiency of the interior surfaces. The interior noise estimates are based on acoustical models for theatre acoustics and on measurement data from other performance halls.

Design Criteria for Performance Halls

The criterion for acceptable noise from exterior sources in state of the art performance halls is frequently the threshold of hearing, sometimes denoted as the N-1 criterion. Although this criterion may seem extreme to some, it ensures that there will be no intrusion from exterior sources during critical recording and allow the performers and audience the opportunity to thoroughly concentrate on the performance. For low-frequency groundborne noise typical of that generated by rail transit systems, with a slow rise and fall time, some have indicated that such noise can exceed the N-1 criterion by some margin before audibility occurs. The criterion for rehearsal halls and general-purpose halls is usually not as stringent and is typically in the range of PNC-15 to 20 (Preferred Noise Criterion Curve) or even higher.

Vibration Control Design

Once it has been determined that the appropriate noise criterion will not be achieved, then various methods to reduce the transmission of vibration into the building and hall are evaluated. Although there are other intermediate methods for reducing the transmitted vibration such as increasing the coupling loss between the ground and building with massive foundation elements or designing floating floors and isolated walls, achieving the N-1 criterion inside a large performance space located near significant groundborne vibration sources requires an effective vibration isolation system design. This amounts to the use of a heavy foundation structure to increase the coupling loss in combination with a relatively low natural frequency structural isolation system to achieve sufficient reduction of the structure-borne vibration which radiates the structure-borne noise in the performance hall.

The main design parameters for a successful design include a rigid, high acoustical impedance foundation of the building structure below the isolation plane, a very low impedance isolation medium with stable structural characteristics and low dynamic stiffness, a stiff high mass structure above the isolators for at least two floors, and resilient lateral restraint for mechanical and seismic stability.

Figure 1 is a schematic diagram showing the essential elements of a high efficiency structure-borne noise and vibration isolation system. Items shown include a heavy concrete foundation slab which is connected to concrete footings or columns; vertical gravity load and lateral restraint isolation bearings; heavy concrete beams and a continuous, relatively thick floor above the isolation bearings and concrete shear walls.

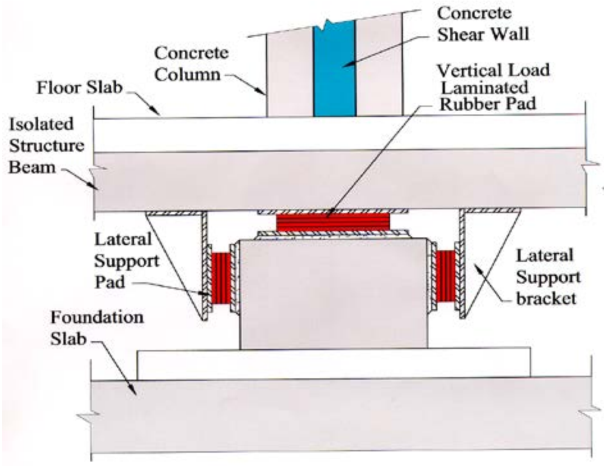

Figure 1. Essential isolation design elements

Additional design elements for a successful design include the need for the floors directly above the isolation to have a fundamental frequency above approximately 15 Hz to avoid potential coincident effects with the resonant frequency of the isolation system, acoustic isolation joints around the full perimeter of the isolated hall (typically 100mm to 150mm wide), resilient service connections across the acoustic joints and resilient closures around doors and across thresholds at acoustic joints.

FOUR SEASONS CENTRE FOR THE PERFORMING ARTS

The Canadian Opera Company had been looking to build a permanent home for many years. Even when the site bounded by University Avenue to the west, Richmond Street to the south, York Street to the east and Queen Street to the north became available, it took many years to procure the funding and decide on a final design on what is now known as the Four Seasons Centre for the Performing Arts (FSCPA). Selection of this location directly adjacent to the Toronto Transit Commission (TTC) subway line under University Avenue and the TTC surface streetcar line on Queen Street led to the belief that there could be groundborne noise and vibration sufficient to cause excess interior noise particularly in the main performance hall, now called the R. Fraser Elliot Hall.

The desire to locate the facility on this downtown site also meant that space was at a premium and the project team needed to work closely to develop a successful design. Wilson, Ihrig & Associates was retained by the lead acoustical consultant/designer, Sound Space Design of London, UK, and worked closely throughout the project with the structural engineers, Halcrow Yolles and the local acoustical consultant, Aercoustics Engineering Ltd., who were responsible for airborne noise control.

WIA was specifically retained to evaluate the site and provide design support so that groundborne noise from all exterior activities would be inaudible in the main performance hall. The goal was that with appropriate control of both groundborne and airborne noise, with the HVAC and other utilities within the hall turned off, the threshold of hearing would be achieved.

Site Evaluation

The initial site evaluation, which took place in January 1999 in conjunction with the local firm, Jade Acoustics, was undertaken to quantify the noise and vibration expected in the new building without vibration isolation. Ground vibration measurements were obtained at eight locations on the building site, with supplemental measurements at six locations in two nearby buildings. Of the measurements obtained on site, six were located on the perimeter and two were located near the centre of the site. The vibration measurement locations were selected to detect the maximum groundborne noise and vibration levels generated by the TTC streetcars travelling east/west on Queen Street West and by the TTC subway trains running north/south beneath University Avenue. No streetcars were observed operating on the tracks on York Street, and it was determined that these tracks are only used for emergencies. A qualitative review of the track and wheel condition of the rolling stock indicated a lack of significant rail corrugation and only occasional wheel flats. Thus it was believed that the measurements indicated vibration measurements that were characteristic for the operation of both the surface streetcars and underground trains.

The recorded vibration data were analysed in terms of 1/3 octave band rms vibration velocity levels which occurred during each train passby. As a basis for the building's interior noise projections, the ground vibration levels measured across the site were combined to determine the range of maximum vibration levels associated with both subway and streetcar transit vehicle passbys. A characterization of the typical *maximum* vibration levels at the site was used in the analysis so that the isolation system would be designed to provide adequate reduction for the typical maximum vibration events.

Figure 2 presents the range and average of the maximum ground vibration levels produced by both the streetcars and subway trains combined. The range and average of vibration levels for all transit vehicles shown in Figure 2 were converted to octave band levels, and used as the basis for projections of radiated interior noise levels for the FSCPA performance and rehearsal spaces.

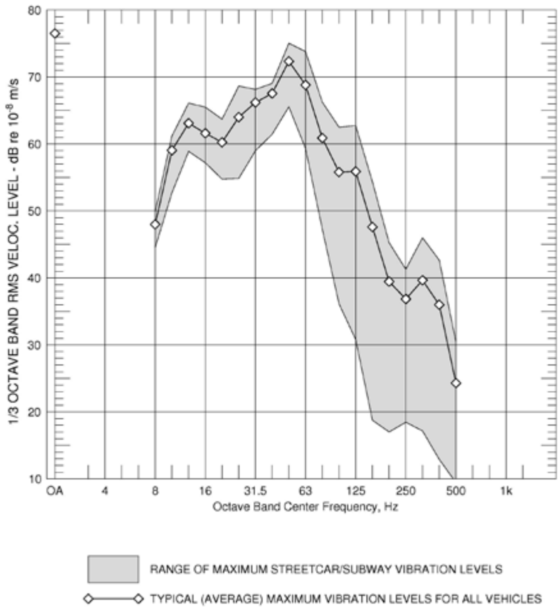

Figure 2. Range of Maximum Ground Vibration Levels due to Passbys of All Rail Vehicles

Groundborne Noise Projections

Figure 3 presents the estimated range of maximum interior noise levels in the main performance hall due to groundborne noise and vibration from all rail transit vehicle operations, compared with the N-1 criterion. Review of Figure 3 indicates that at least 25 dB of additional attenuation of ground vibration at 63 Hz and higher frequencies would be needed to achieve noise levels at or below the threshold of hearing.

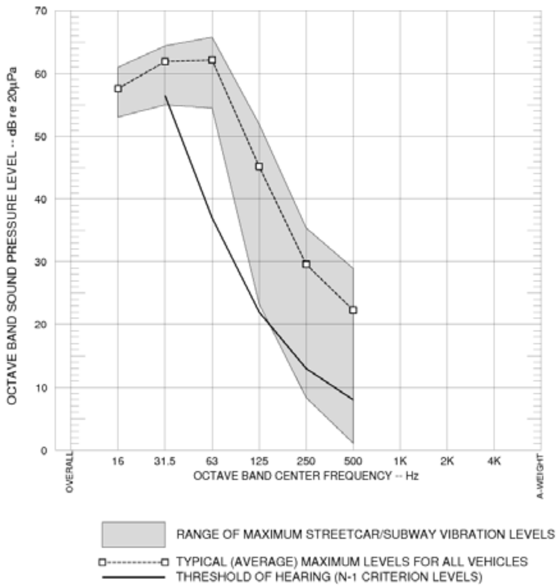

Figure 3. Range of Maximum Estimated Radiated Noise Levels Inside Main Hall without Isolation

Based on the results presented in Figure 3, mitigation in the form of full vibration isolation of the performance space and rehearsal hall structure from the ground was recommended. This vibration isolation is practically achieved by supporting a stiff and massive structure on resilient rubber bearings using a box-in-box design. The isolation system must provide a resilient support which will reduce the structure-borne noise from the trains, transmitted via the foundation elements and building structure, by a sufficient amount to reduce the noise in the performance and rehearsal areas to a satisfactory level. WIA determined that the required isolation could be achieved with the natural rubber bearings if the building structures immediately above and below the bearings in the isolation plane were extremely stiff and massive. Using a rubber pad isolation system alone would not provide sufficient attenuation to reduce the background noise levels to achieve criteria compliance.

In theory, vibration isolation is provided at frequencies above the natural frequency of the single-stage isolation system, and the vibration reduction increases with vibration frequency. In reality there is a point above the natural frequency where the reduction stays relatively constant with increasing frequency. So the reduction necessary must be achieved at the most critical frequency, i.e., the 63 Hz octave band. During preliminary design, it was determined that the appropriate reduction at this most critical frequency would require the isolation bearing pad system for the main performance hall be designed to provide a vertical natural frequency of 4 to 5 Hz. Later, during detailed design, it was determined that a system with a vertical natural frequency of 6 Hz would be satisfactory for the main hall considering the structural loads, space available to place the pads, constructability and pad strain. Figure 4 presents the expected noise levels in the main performance hall using a system with a vertical natural frequency of 6 Hz.

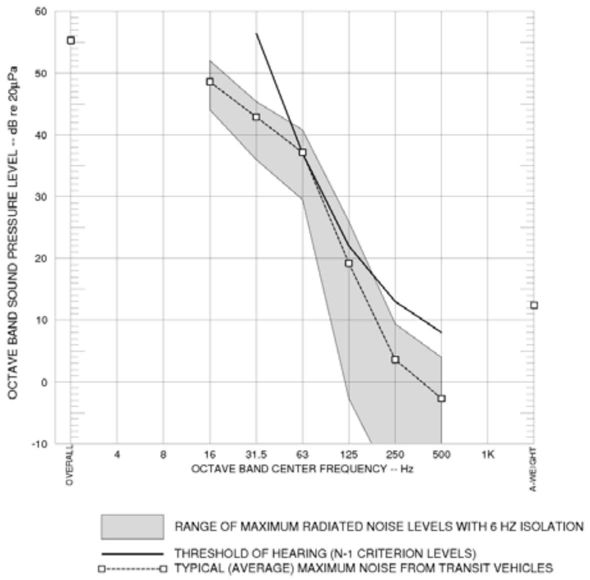

Figure 4. Projected Maximum Interior Radiated Noise Levels with 6 Hz Isolation System

Although the focus was on the groundborne noise reradiated from the generated vibration, it was important that the vibration be imperceptible. The expected vibration levels without any mitigation were expected to just approach the lower limit of perceptibility. However, with the rubber bearing pad isolation system, as designed, the vibration levels were expected to be well below the minimum levels of perceptibility and thus there would be no perceptible vibration inside the performance or rehearsal halls from any sources outside the halls.

Since the building incorporates an underground parking garage, the so-called acoustic joint or isolation plane was located above the garage, so that structure-borne noise and vibration from vehicles in the garage would also be isolated. This isolation joint continues up in the vertical direction around each hall so that the halls would be isolated from the remaining building areas. It is important that there be no structural bridges, thus all utility and other building and finish service elements which pass from the non-isolated areas to the isolated performance areas include resilient joints or flexible connectors. The structural isolation also continues to the upper levels of the hall where the cantilevered walkways for accessing the balconies are supported on rubber pads since the walkways connect to the isolated structure of the main hall.

The Canadian Opera Company also elected to vibration isolate the rehearsal hall which is located on the north side of the building immediately adjacent to the streetcar tracks. This was necessary in order to achieve a background noise criterion equivalent to PNC-15 to 20. Although this criterion would mean that the passing streetcars would not be totally inaudible, their passage would not be intrusive. However, accomplishing this task presented an interesting design problem, as the pads would not be accessible from below the floor of the hall due to structural considerations for the parking garage street access. The solution was to place the isolation pads in the isolation plane beneath a structural steel framework which would support the floor for the rehearsal hall. The floor consists of relatively massive pre-cast concrete beams that were set on the steel framework. A finish floor layer applied above the beams then tied the precast beams together. This same design was also used for the side stage portion of the main hall.

Isolation Pad Design

Although various elastomer materials are available, WIA has found that natural rubber provides the best characteristics for building isolation applications, a low ratio of dynamic-to-static stiffness, a very low creep rate under compression load and very long service life without deterioration or stiffening of the elastomer material. Many synthetic materials have limited service life, particularly under constant compression load. Also, the ratio of dynamic-to-static stiffness is significantly higher with synthetic elastomers. This results in higher static strain in the elastomer for the same basic natural frequency of the isolation system. It has been shown that natural rubber lasts for many years without deterioration and full retention of the load support capability and resilience. Thus, the isolation designs do not require provision for maintenance and replacement of the rubber pads, although in most instances, the designs are arranged to provide access for checking the condition in the future.

The actual design of the natural rubber pads can only be done after the general arrangement and structural loads characteristic of the building have been determined. With this information a preliminary design can be developed. An iterative process between the structural engineers and WIA then determined the locations where the pads could be placed and the specific sizes of pads that would be used.

For the main hall, including the side stage, there are almost 350 vertical load bearings ranging in size from 250mm x 250 mm (10" x 10") to 600mm x 600mm (24" x 24"), with 85% of the bearings being 450mm x 450mm (18" x 18") and 500 mm x 500 mm (20" x 20"). The bearings are 173 mm thick (almost 7"), with 4 layers of laminated rubber separated by 3mm steel plates. Typical deflection is 9.5 mm (3/8") under the static dead load of the inner box structure, while the typical live load could increase this to approximately 12.7 mm

(1/2"). This system is capable of handling much greater live loads should they ever occur. The dead load natural frequency of the isolation system is approximately 6 Hz, while typical dead load strain is less than 7%. Figure 5 shows the typical configuration for the vertical load rubber isolation bearings.

For lateral restraint, there are 80 horizontal load bearings, 450mm x 450mm (18" x 18") in plan of 181mm (just over 7") thickness with steel end plates. These are set in orthogonal pairs for control of lateral motion up to .12 g. Figure 6 shows the configuration for the horizontal load bearings. The lateral bearings are all preloaded in compression to 10 mm (2/5") so that they remain in compression during any normal range of lateral motion expected at the site.

For the rehearsal hall, there are 36 vertical load bearings of two sizes, 250mm x 300mm (10" x 12") and 300mm x 300mm (12" x 12"). These bearings are marginally thicker than those for the main hall, as they incorporate two additional steel plates at the top for attachment to the steel framing which supports the floor. The 24 lateral restraint pads for the rehearsal hall and side stage are 250 mm x 250 mm (10" x 10") and are also set in orthogonal pairs.

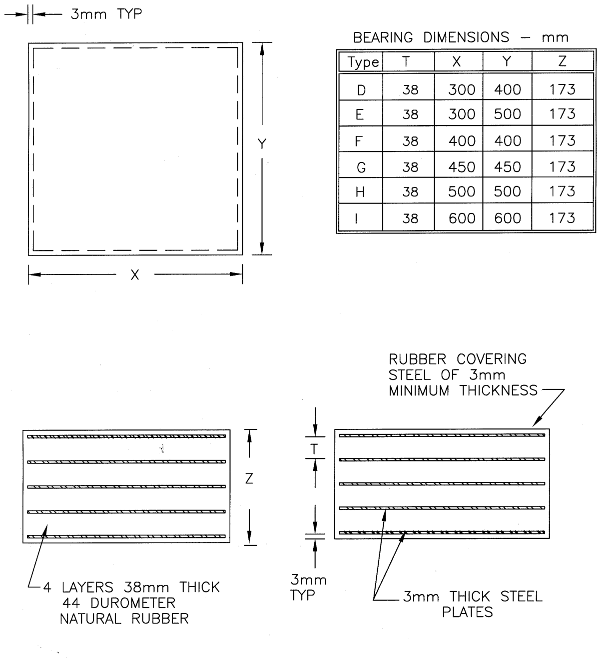

Figure 5. Typical Configuration for Vertical Load Rubber Isolation Bearings for Assemblies with Grout Pads Below and Above Bearing Pads

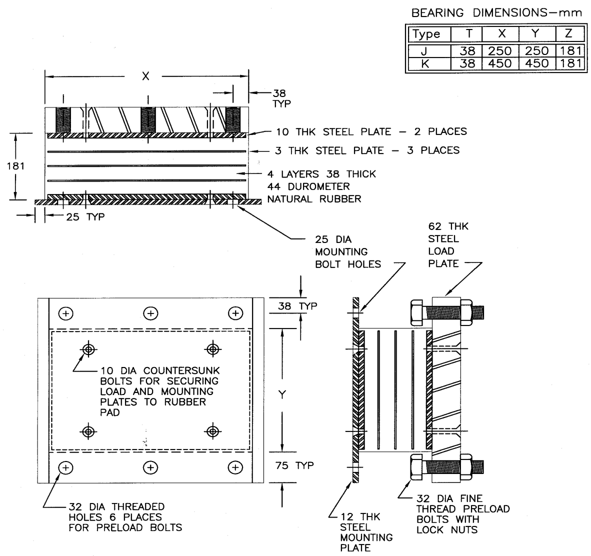

Figure 6. Horizontal Restraint Bearing Configuration with Provision for Preload Compression Adjustment

Construction

Construction at the site started in 2003 and the hall was finished in 2006. Scougal Rubber of Seattle produced the pads and they were shipped to Toronto where the contractor stockpiled the various isolation pads until needed. The pads providing support for the main hall had to be placed relatively early in the construction process, since the isolation plane is located at the foundation level or just above the garage. Figure 7 shows a group of the rubber bearing pads prior to pouring the concrete that supports the isolated portion of the main hall.

Figure 7. Group of Rubber Pads Prior to Pouring Concrete Supporting the Main Hall

During the pouring process, sand is used to fill between the pads to keep out the concrete and is later removed. Figure 8 shows how the sand is used as part of the forming process.

Figure 8. Group of Rubber Pads with Sand Filling the Gap between the Support Pads, Prior to Installation of the Top Grout Pads

As construction progressed, the support pads would begin to compress as more mass was added. Full deflection was then achieved after all of the building elements were added to the isolated portion of the structure. Figure 9 shows a group of isolation bearing pads after installation and loading.

Figure 9. Bearing Pads after Installation and Loading

The four layers between the steel plates in the pad bulge out when loaded. The lateral restraint pads were preloaded using a hydraulic jack and a locking bolt/nut system attached to the steel plate on the pad. This process was accomplished in 2005 after most of the expected dead load was on the isolated part of the building to minimize the shear load on these side pads. Figure 10 shows the hydraulic jack and process used to preload the lateral restraint pads. Figure 11 shows a partial top-down view of a side pad after compression preloading.

Figure 10. Hydraulic Jack used to preload the Lateral Pads

Figure 11. Partial View of Lateral Restraint Pad after Compression and Loading

Noise and Vibration Reduction Results

Following substantial completion of the building, noise and vibration measurements were obtained in April 2006 to assess the background levels in the hall from structure-borne noise and the reduction of vibration achieved by the isolation design. Thus, these measurements were obtained with the HVAC and other auxiliary systems off. In the main hall, simultaneous noise and vibration measurements were obtained at two locations. During these measurements, vibration measurements were also obtained in an unisolated area outside the hall to positively identify high level vibration events, most of which were from TTC surface streetcar and subway train operations. Figures 12 and 13 present the results of the noise measurements during train passbys in terms of octave band levels and slow meter response. These are compared with measurements of ambient noise in the hall and the N-1 or threshold of hearing curve. The data are presented only through the 125 Hz octave band, as the data above the 125 Hz octave band during train passbys are clearly not from trains since the data match the ambient data without trains passing by. Also, the data above the 125 Hz octave band was not optimized for signal-to-noise ratio, as this was done only for the low frequency data, so the higher frequency data are not shown, since these data are thought to represent the noise floor of the measurement equipment and not the true ambient of the hall at these higher frequencies.

Review of Figures 12 and 13 indicates that the noise data fall right at the N-1 curve. Although the range of the data shows maximum levels are just above the N-1 curve, this is not deemed significant, as all of the train passbys during the measurements were completely inaudible to those in the hall, even when the vibration transducer monitoring vibration outside the hall clearly indicated that a high level vibration event, such as a train passby, was occurring. In addition, the spectrum of the train passbys change as the trains pass such that the maximum levels in the various octave bands on the curve do not occur simultaneously, thus showing the range of the data may be somewhat misleading in terms of determining audibility.

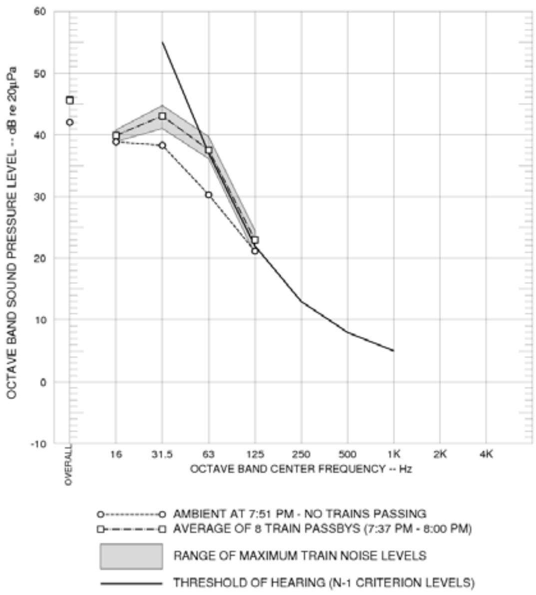

Figure 12. Maximum Noise Levels at North Aisle – Row D

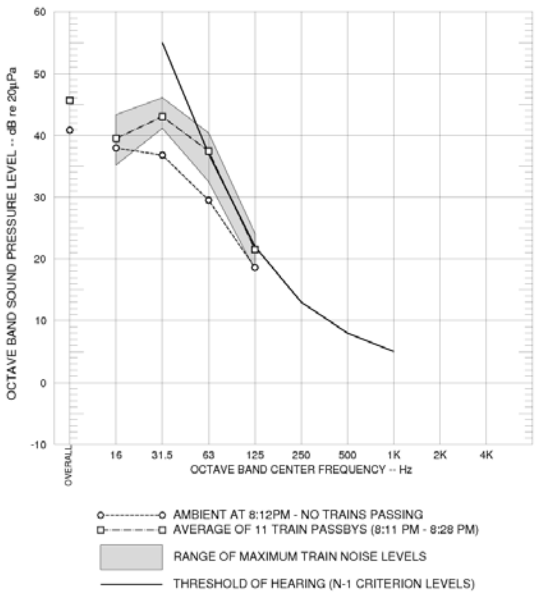

Figure 13. Maximum Noise Levels at North Aisle – Row W

Vibration measurements were obtained at 7 locations. Measurements at all locations indicated that the measured vibration levels are well below the level of human perception at all times. Vibration measurements across the acoustic joint indicated that vibration reduction was achieved at all measurement locations where these measurements were obtained. Figure 14 shows one of the vibration measurements across the acoustic joint in an exit corridor. Figure 15 shows one of

Figure 14. Vibration Measurement across the Acoustic Joint in an Exit Corridor

Figure 15. Vibration Measurement across the Acoustic Joint at a Foundation Element

the vibration measurements across the acoustic joint at a foundation element. The most significant and characteristic reductions were achieved where the vibration levels from the trains were highest. This included measurement locations closest to the subway at the west side of the building just outside the rear of the hall at the lower lobby level and at the southwest side of the building just outside the south side of the hall in an exit corridor. Somewhat lower levels of vibration reduction were measured across the acoustic joint at the northwest entrance to the side stage, under the rear stage area near the mechanical equipment rooms and at the west closet of the rehearsal hall. It is believed that these results were due to having lower source vibration levels, other activities occurring during the measurements on the isolated sections and possibly unusual modal characteristics at the chosen measurement locations. Although no noise measurements were obtained during this series of measurements with the exception of those in the main hall, it is believed that the background noise criterion will be achieved in the side stage area and rehearsal hall based on the vibration measurements.

Figure 16 shows the vibration reduction in terms of octave bands achieved at two of the measurement locations closest to the subway. The reduction achieved is shown in comparison with the design curve used for a 6 Hz isolation system.

This figure is indicative that the expected vibration reduction was achieved with the vibration isolation system as designed.

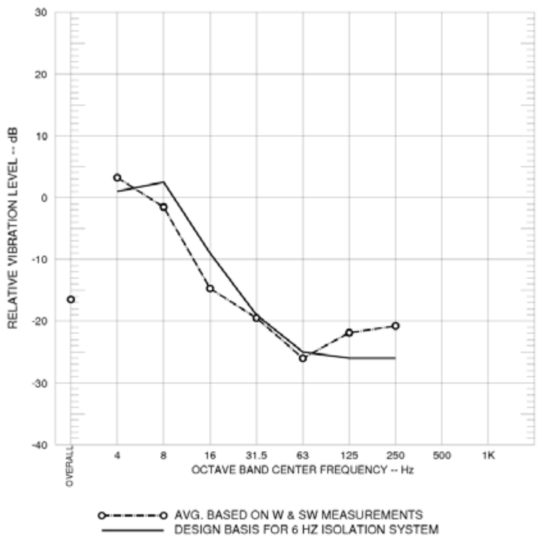

Figure 16. Structure/Groundborne Vibration Reduction Closest to the Subway Compared with the Design Curve

CONCLUSION

The overall design procedure and the requirements which have been developed make it possible to successfully build noise-critical spaces such as performing arts facilities in locations where there is severe impact due to groundborne noise and vibration from transportation facilities. With appropriate consideration of the structural configuration, of the isolation design system natural frequency and the acoustical impedance mismatch between the rubber pads and the structure both below and above the isolation bearings, it is possible to achieve even the most restrictive design criteria for interior radiated noise. Figure 17 shows the finished FSCPA as it looks today.

Figure 17. Four Seasons Centre for the Performing Arts

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