

Acoustics'08
Paris
June 29-July 4, 2008

www.acoustics08-paris.org

euronoise

Building Isolation Design for Noise Critical Applications

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Because it is a complex, multi-degree-of-freedom system, the success of a building isolation installation depends on careful selection of a number of design factors. The new Toronto Opera House, the Four Seasons Centre for the Performing Arts, opened in June 2006, is located directly adjacent to a surface light rail trackway and to a subway rail transit system. The results, characterized as “the quietest Opera House in the world”, demonstrate that groundborne noise and vibration is not a factor precluding the use of a noisy site for a noise-sensitive facility. Measurement of the existing groundborne noise provides a basis to determine the required noise reduction. Using very stiff and massive foundation elements with stiff and massive structure directly above the isolation bearings allows the isolation design to be simplified to a single-degree-of-freedom system for deriving the performance of the isolation at low frequencies. Natural rubber bearings with thickness adjusted to provide a large amount of insertion loss for the structure-borne noise can be used to determine the expected performance at frequencies above 50-80 Hz. Isolation system design parameters for the new 2000-seat Opera House Performance Hall and graphical results from vibration and noise tests are presented.

1 Introduction

Location selections for many new concert hall and theater projects are frequently based on criteria unrelated to the potential for good overall acoustics as can be readily achieved at a quiet site. Requirements for proximity to other pre-existing cultural venues, such as art museums, other concert halls or theaters and central location in a city frequently override the desire for site free of exterior airborne and groundborne noises which can adversely affect the ambient noise within a completed performance hall. In North America there have recently been several new concert halls and theaters which are located in very close proximity to railroad or rail transit facilities and high traffic flow roadways. The groundborne and structure-borne noise inherent with such locations requires that the site be made acoustically compatible or acceptable through introduction of structural vibration isolation of either the entire building or of the performance hall within the building, creating a box-in-box type of structure.

In Europe there has been a history of vibration isolation of buildings, both performance hall and residential buildings using natural rubber pads, synthetic elastomers or steel springs as the isolation element. Many of these projects were successful in controlling the noise interior to the building and the technology provided basic background for the development of isolation systems providing for very low interior noise. The motivation for providing even higher than traditional degrees of isolation was the fact that many of the modern concert hall acousticians require an extremely low background noise level, the threshold of hearing, sometimes denoted the N-1 Criterion.

The development of structural isolation design configurations to achieve a greater degree of isolation than typical or traditional was partially based on the detailed technology that was developed in the 1970's and 80's for floating slab trackbed systems intended to decrease the transmission of groundborne vibration and noise from rail systems to adjacent properties. In many instances these floating trackbed or vibration isolated trackbed systems were designed to assure that the noise from a new rail system installation would not be audible in existing buildings adjacent to the new trackway or subway. The designs for the rail isolation systems were based on the use of multi-stage or multiple-degree-of-freedom isolation systems with careful adjustment of mass and stiffness ratios to make the successive parts or stages of the system have complimentary performance. Another part of the design

technology was to use very low damping factor elastomeric bearings to maximize the isolation effect at low frequencies and to achieve acoustic impedance mismatch at higher frequencies. Use of low damping elastomer bearings is to prevent the coincidence and resonance effects which can occur with steel spring systems and/or with multi-degree-of-freedom systems that do not have individual resonances adequately separated. Resonance coincidences or interactive performance can significantly reduce the effectiveness of an isolation installation.

With the information developed over an approximately 15-year period of working with the design, measurement and improvement of rail system isolation, used in combination with the information from earlier or existing building isolation projects in Europe and North America, a design using thick cross-section natural rubber bearing pads as the isolation medium was derived. The objective was to achieve an economical and effective isolation system for projects with a very low background. Generally, the goal is that with appropriate control of both groundborne and other structure-borne noises, within the hall, the exterior noises will be reduced to the threshold of hearing with the HVAC and other utilities turned off. To achieve this goal with respect to groundborne noise, the general design approach is:

1. Completion of a groundborne vibration survey at the site to determine the vibration levels at the base or foundation for the new building.
2. Projection of expected structure-borne noise in the performance hall(s) considering the type of foundation and structure proposed for the building and considering other potential structure-borne noise sources in or near the building.
3. Comparison of the expected structure-borne noise radiated into the new performance facility with the criterion for acceptable noise from exterior sources. This then defines the amount of noise reduction or insertion loss the isolation design must achieve.

When there is expected structure-borne noise exceeding the criterion, the next steps consist of:

4. Cooperative work with the structural engineers for the project to determine appropriate structural modifications for incorporating an effective structure-borne noise isolation system in the overall building design.
5. Design of an isolation system and bearing configuration to control the structure-borne noise and vibration so that it will not exceed the design

criterion which for most recent concert halls and opera houses has been the threshold of hearing.

2 Site Evaluation

The initial step in the design process for achieving very low background noise inside a facility located in a noisy area is measurement, analysis and evaluation of the groundborne vibration and noise at the site. In some cases, this requires performing measurements in boreholes drilled to the expected depth of the new facility foundation. In other cases, measurement of the groundborne vibration at the surface and inside nearby buildings with similar depths of foundation is sufficient.

For the Four Seasons Centre for the Performing Arts, FSCPA, project in Toronto, because there were several buildings available around the site with similar foundation depths, measurements were made only at the surface on the site and in buildings adjacent to the site. These measurements were done in 1999 by Jade Acoustics located in Toronto. For ground surface measurements and for measurements inside existing buildings, the vertical vibration shows the best correlation for vibration transmitted into buildings. Therefore, the surface and in-building measurements were of only the vertical vibration.

Figure 1 is a layout drawing showing the location of the FSPCA building directly adjacent to the University Avenue subway and the Queen Street light rail line. The vibration measurement locations at the surface and within nearby buildings are indicated. The site was an existing, undeveloped block of land with an ideal center city location.

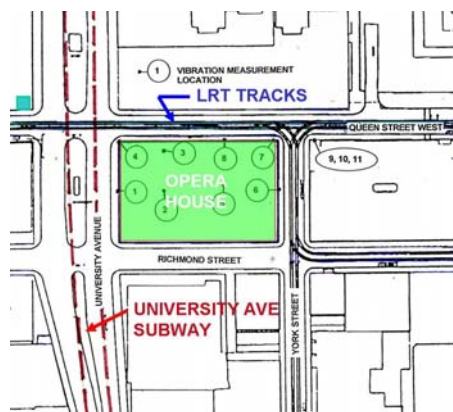


Fig. 1 Layout at Toronto Opera House Showing Adjacent Subway and Light Rail Lines

The vibration measurement locations were selected to evaluate the maximum groundborne vibration and noise levels generated by the light rail vehicles traveling east-west on the adjacent Queen Street West and by the subway trains running north and south along adjacent University Avenue. The recorded vibration data were analyzed in terms of 1/3 octave band rms vibration velocity levels which occur during the time of each train passby. The data measured across the site were combined to determine the range of maximum levels associated with both subway and light rail vehicle passbys. As in all performance hall type evaluations, the typical maximum rms vibration levels at the site were used in the analysis.

In interpreting the measured vibration data, particularly for the surface measurements and for derivation of correction factors, such as the building foundation coupling loss, it is important to recognize that data from each individual location can be affected by local conditions. Thus, it is absolutely necessary that vibration measurements be taken at multiple locations to be sure of obtaining representative measurements of the ground vibration. Small-scale localized variations which may affect the vibration measured at individual locations are not significantly reflected in the overall noise radiated by a large surface such as the floor or wall of a performance space. The vibration of a building and the noise radiated into the space are averaged effects over the surfaces of the building structure or interior space. Thus, for the site evaluation, multiple measurements at different locations on the surface at the site and multiple locations in nearby buildings are required to be sure of obtaining representative vibration exposure for the new facility. Figure 2 presents the envelope of typical maximum groundborne vibration levels from the LRT trains and subway trains at the FSPCA site in Toronto.

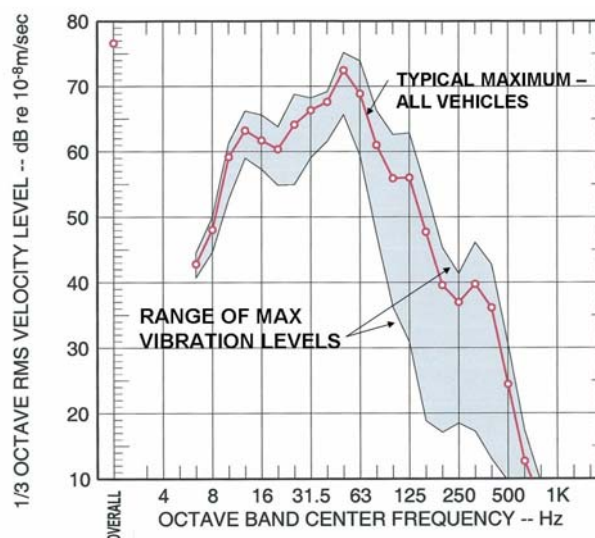


Fig. 2 Range of Maximum Groundborne Vibration Levels due to LRT and Subway Trains

3 Groundborne Noise Projections

Starting with the measured vibration levels, the next step in determining the vibration isolation design is to estimate from the measured vibration levels at the foundation level the expected noise levels within the building without consideration of any vibration or noise isolation. This requires information from the structural engineers and architects on the planned configuration of the foundations and the structure between the foundations and the performance hall space. The first part of that estimate is calculation of the expected coupling loss between the ground and the building foundation and basement structure.

The second part of the estimate of vibration levels at the performance hall floor and walls is accounting for the amount of structure or number of floors between the foundation and the performance hall. The general practice is that the amount of attenuation as the structure-borne noise and vibration transmits up through the building is assessed in terms of the attenuation per floor. For point

sources, such as fans or pumps, or even automobiles in a parking structure, this attenuation can be significant. However, because transit vehicles are long line sources with the groundborne vibration transmitting into the building from the numerous wheel and axle sets, the general effect is that of a line source and the result is very little attenuation per floor. In an all-reinforced concrete building the attenuation per floor is less than 1 dB. In a typical composite concrete/steel building the attenuation is about 1 dB per floor at low frequencies and up to 2 dB per floor at frequencies above about 125 Hz.

The third step in estimating the vibration levels at the performance hall floor and wall is the consideration of potential structural resonance causing an increase in the vibration level, particularly towards the center of large span floors. For lightweight composite steel/concrete structures the floor amplification can be as much as 5 to 10 dB. However, for the heavy concrete floors and walls which are typical of concert halls and other larger performance halls, the amplification factor is in the range of 0 to 5 dB, generally 3 to 5 dB for small venues such as theaters and 0 to 3 dB for large concert halls and opera houses.

The final step in calculating the expected noise is converting the vibration velocity level of the floor and walls of the performance space to noise level radiated into the space. For the typical room volumes and sound absorption present in performance halls, the reverberant sound level in the room is usually within 2 dB of the value calculated for a plane wave radiated directly by the floor surface.

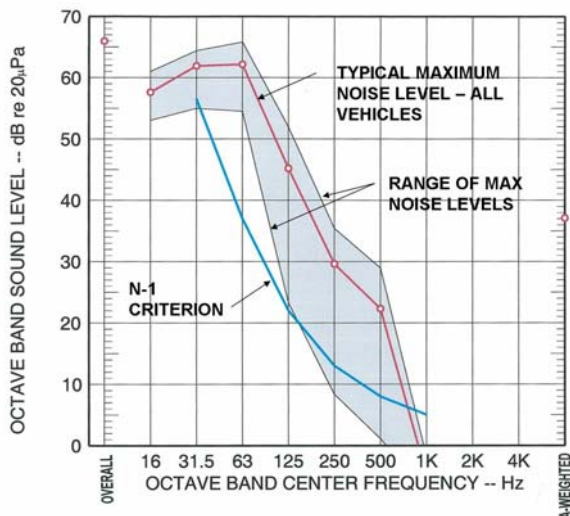


Fig. 3 Range of Maximum Estimated Noise Levels Inside Main Hall due to LRT and Subway Train Passbys

With the four main correction factors applied, the coupling loss, the attenuation through the building, the structural amplification factor and the conversion to sound level in the performance hall, the expected sound level without vibration isolation can be derived. Figure 3 presents the sound levels projected for the main performance hall at the Toronto Opera House based on the vibration measurements at the site and at the adjacent buildings. While the measurements and calculations are made on a 1/3 octave band basis, for comparison with audibility criteria which are generally expressed in terms of octave band levels, the calculated sound levels are converted to octave bands. Figure 3 also indicates the N-1 criterion curve, the

threshold of hearing, which is the design goal for the project. As is evident from the projections shown by Figure 3 a reduction of about 24 dB is required at the 63 Hz octave and higher frequencies. Keeping in mind that the projection, as shown by Figure 3, includes the effect of coupling loss and the other building factors, the graph indicates the degree of isolation or insertion loss that must be provided by the structural vibration isolation system.

4 Vibration Isolation Design

Figure 4 presents a graph indicating the typical insertion loss which can be achieved with isolation systems designed for 4 Hz natural frequency and for 6 Hz natural frequency based on the dead load equivalent mass loading the rubber pads. The 4 Hz curve is based on actual results achieved with natural rubber pads having 180 mm total thickness. For the 6 Hz isolation system, the insertion loss is based on bearing pads having 150 mm total rubber thickness. Considering the expected results from the 6 Hz system, this was the design recommended and adopted for the FSPCA project.

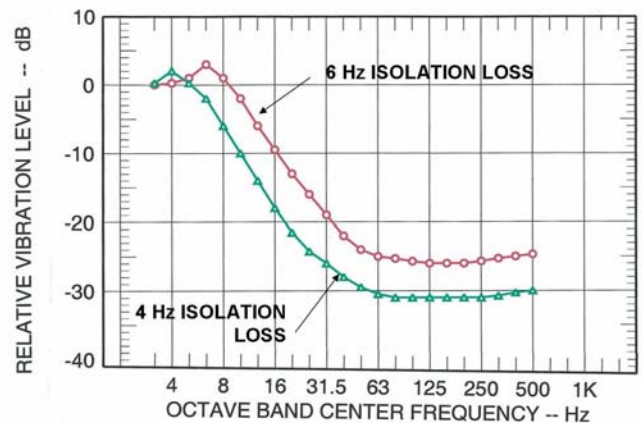


Fig. 4 Expected Insertion Loss or Isolation Effect of a 4 Hz and a 6 Hz Design

In order to achieve the performance indicated by Figure 4 it is necessary that the structural beams and floors directly below and directly above the isolation bearing pads be massive and stiff. For the structure above the bearings the general requirement is that all beams be either reinforced concrete or concrete encased steel beams and floors be 300 mm thickness concrete designed to provide a fundamental natural frequency of 15 Hz or greater. The requirement for the heavy concrete construction extends at least for two levels above the isolation plane. For the foundation elements below the isolation plane, similar requirements apply.

Figure 5 presents the expected noise levels in the FSPCA main performance hall using an isolation system with rubber pads designed to provide a natural frequency of 6 Hz for the calculated dead load at each support location. In this case, since the building incorporates an underground parking garage, the acoustic joint or isolation plane was located at the top of the garage structure so that noise and vibration from vehicles and equipment in the garage levels would also be isolated.

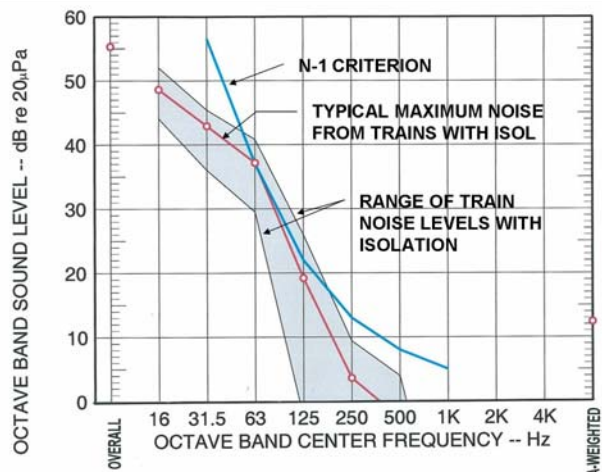


Fig. 5 Projected Maximum Estimated Noise Levels Inside Main Hall due to LRT and Subway Train Passbys With 6 Hz Isolation System in Place

5 Isolation Pad Design

Although various elastomer materials are available which can have mechanical characteristics adjusted to the 6 Hz design requirement, past experience with rail system floating track slabs and building isolation projects indicates that the best characteristics for building applications are a natural rubber compound with a low ratio of dynamic-to-static stiffness and a very low creep rate under compression load. With appropriate selection of service load, a very long service life can be expected without stiffening or deterioration of the natural rubber pads. Most synthetic materials have limited service life, particularly under constant compression load.

For an isolation system with very low damping factor, because the vertical load support pads have very low stiffness in the horizontal direction, it is necessary to provide lateral restraint bearing pads. The lateral pads provide both for mechanical stability of the isolated structure or box and provide for restraint in the event of any seismic motion or lateral load from wind loads on exposed structure. The lateral pads are always arranged in orthogonal pairs and preloaded to provide that they remain in compression during any normal range of lateral motion expected at the site.

For the FSPCA main hall there are 350 vertical load bearings ranging in size from 250 mm to 600 mm sq. Typical dead load deflection is 10 mm. For lateral restraint at the main hall, there are 80 bearings 450 mm sq and of the same thickness of rubber as for the vertical pads. These are placed in orthogonal pairs for control of lateral motion up to 0.12 g.

To achieve the very low ratio of dynamic-to-static stiffness, less than 1.40, and to achieve the very low creep rate under compressive load, less than 1.5% of initial deflection per decade of time, the rubber pads are specified to be in accordance with a formulation first created in 1972 by the Malaysian Natural Rubber Bureau in UK. This formulation has been proven to be a high quality material readily produced by a number of natural rubber component suppliers in North America, UK, Australia and the Far East. To be sure of a long service life for the building isolation, the loading of each bearing pad is limited to 2.8 kN/m²

stress and a dead load strain of not more than 7%. The size of each bearing is determined by these stress and strain limitations and, for the FSPCA project, a calculated resonance frequency of 6 Hz based on the dynamic stiffness and mass equivalent to the dead load at each support location.

Figure 6 is a photograph showing a group of rubber pads after pouring the concrete structure that supports the isolated main hall and full loading by the hall above. During the pouring process, sand is used as fill between and around the pads to maintain the free space. After the concrete has cured, the sand is removed. As construction progresses above the pads, the support pads compress as mass is added. Full deflection is achieved after all the building elements are added to the isolated portion of the structure. Figure 7 shows the configuration of the lateral pad assembly with loading bolts.



Fig. 6 Isolation Bearing Pads after Installation and Loading



Fig. 7 Lateral Bearing Pad Configuration

6 Noise and Vibration Reduction Results

Following completion of the FSPCA building, noise and vibration measurements were obtained in April 2006 to assess the resultant background noise levels in the main performance hall due to structure-borne noise and to determine the actual reduction of structure-borne noise and vibration achieved by the isolation design. Simultaneous noise and vibration measurements were obtained at two

locations also at non-isolated areas of the building outside the hall to positively identify high level structure-borne vibration and noise events. Figure 8 presents the results of the noise measurements representing the average of two locations, one at Row D and one at Row W in the audience area. Figure 8 also includes the ambient noise measured in the hall and the N-1 criterion curve.

As is apparent on Figure 8, for the frequency range of the 63 and 125 Hz octaves, the train noise results are essentially right at the N-1 curve with a few maximum levels 1 or 2 dB above the N-1 curve. This was deemed not significant because all of the train passbys during the measurements were inaudible to those in the hall, even when the vibration transducers monitoring vibration outside the hall clearly indicated a high level vibration event such as a train passby. On Figure 8 the data above 125 Hz are not shown because it represented the noise floor of the measurement equipment and not the true ambient of the hall at the higher frequencies.

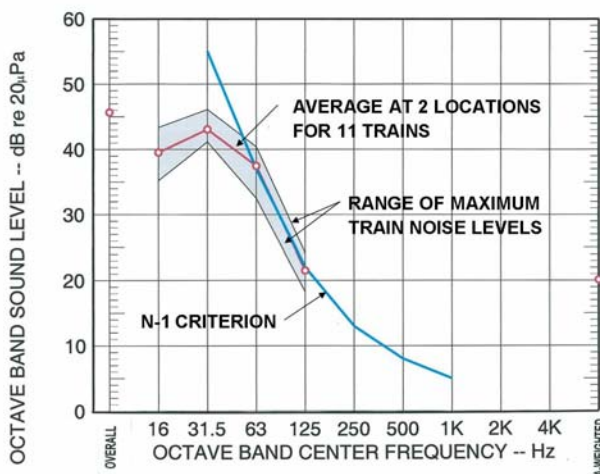


Fig. 8 Measured Maximum Noise Levels Inside Main Hall due to LRT and Subway Train Passbys with 6 Hz Isolation System in Place

Vibration measurements were obtained at seven locations and all indicated that the vibration levels are well below the level of human perception at all times. The vibration measurements across the acoustic joint also indicated that vibration reduction was achieved at all measurement locations. The most significant and characteristic reductions were observed for locations where the vibration levels from the trains were highest. This included measurement locations closest to the subway at the west side of the building

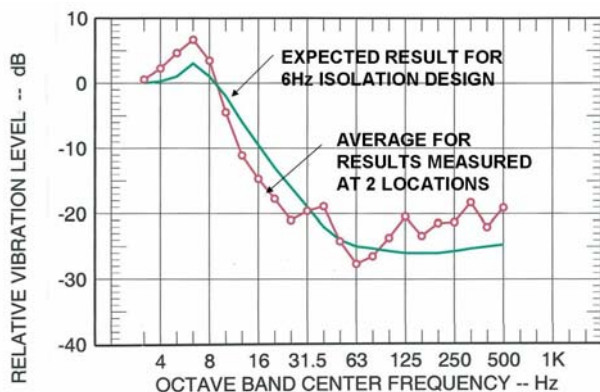


Fig. 9 Measured Insertion Loss or Isolation Effect of the Isolation System

Figure 9 presents the results of the vibration measurements considering the difference in vibration level at the isolated portion of the building compared to the vibration level in the nearby unisolated section. Figure 9 also includes the expected performance for a 6 Hz design isolation system. Review of the measurement results shows that the expected vibration and structure-borne noise reduction was fully achieved with the vibration isolation system as designed. Construction managers have indicated the total cost for structural modifications and the rubber bearing pads is about 2% of the project construction cost.

7 Conclusions

The overall design requirements and procedures which have been developed over the last 20 years have made it possible to successfully and economically place noise critical spaces such as performing arts facilities and residential buildings at sites where there is severe impact due to groundborne noise and vibration from transportation facilities or other sources. With appropriate structural configuration and isolation system design natural frequency, along with using natural rubber pads to create noise reduction between the foundation and the isolated structure, it is possible to achieve even the most restrictive design criteria for interior radiated noise. In some cases it is necessary to have a two-stage system with the first stage a massive concrete foundation to increase the coupling loss to the building compared to a normal building structure and the second stage being the natural rubber pad isolation system. Projects using the design principles developed for building isolation have resulted in configurations ranging from only extra mass in the foundation system to increase coupling loss to designs with very heavy supplemental mass at the foundation and rubber pad isolation system with natural frequency as low as 4 Hz.

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