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Vibration Mitigation Design for an Academic Building Adjacent to a Turbine-Generator Power Plant

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A university teaching and research building was proposed on a site adjacent to a campus steam-turbine power generation plant. Ground borne vibration levels measured on the site confirmed strong tonal peak frequencies of potentially disturbing vibration at the rotational rates of the steam turbine and generator.

The ground borne vibration was analyzed relative to vibration criteria for potential disturbance of vibration sensitive equipment, perception by occupants, audible radiated structure borne noise in acoustically sensitive spaces and visible "jitter" or resolution-degrading motion of projected images in the lecture auditorium and seminar spaces. Based on findings, vibration mitigation design elements were developed for structural and mechanical engineering and for building architecture.

This case study will discuss the desired vibration and noise control objectives and the design solutions that were implemented. Concepts will be presented for isolating, damping or de-tuning building components from ground borne vibration transmission, along with limitations and constraints in the design and construction process. Recent post-construction measurement results will be graphically compared with pre-construction conditions to demonstrate apparent degree of success in mitigating vibration.

1. INTRODUCTION

1.1 Proposed Building and Existing Conditions

An academic teaching and research building was proposed at the University of Texas at Austin. It was to be named Applied Computational Engineering Sciences (ACES), and would house a three dimensional (3D) Visualization Laboratory, Electronic Seminar, Auditorium, numerous computer seminar rooms and offices for faculty and graduate student researchers. Large image rear-screen projection systems were planned for the auditorium and electronic seminar. The visualization lab would have 360° continuous large image projection screen. All of the computer seminar and offices would have desktop computers. The concentrated use of video monitors and projected images throughout the building required stability and resolution of images for optimal viewing without user fatigue (from blurring or screen "jitter"). Perceptible, or "feelable" vibration could also be an occupant annoyance. JEAcoustics (JEA) was retained to provide vibration and noise consultation. Control of those factors became prime parameters for the engineering and architectural building designs.

The ACES building site is located immediately adjacent to the university's electrical power generation plant. A large steam turbine-generator, operating at 3600 rpm (60 Hz), and driven by a 5400 rpm (90 Hz) steam turbine causes strong discrete frequency (tonal) vibration, which is efficiently transmitted to nearby foundations via a deep strata of limestone that lies below the plant and surrounding area. The fundamental and harmonic frequencies of 60, 90, 120, 180 and 240 Hz, measurable in other buildings, would have to be minimized in the ACES building.

http://www.Aces.UTexas.edu/Project Book/Project Book.pdf

Figure 1A. *ACES Building, North View*

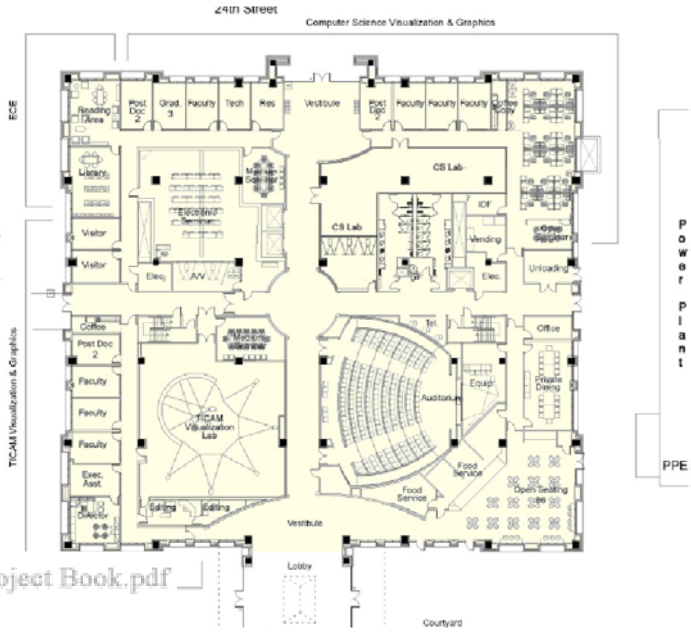

Figure 1B. *Main Floor Plan*

1.2 Design Criteria

A criterion for allowable floor vibration was set for 72 dB, re: 1 μ-inch/sec (.025 μm/sec), based on potential disturbance to projected visual images (up to 100X magnification) and occupant perception (derived from C. Gordon).[1] ASHRAE Noise Criteria (NC), with a 65 dB maximum in 16 – 63 Hz octaves, were implemented for permissible continuous background noise from building systems[2], to minimize airborne sound induced vibration in lightweight structures, such as walls, ceilings or projection screens. Surface vibration levels capable of radiating audible noise from walls, floors and ceilings were considered with regard to Noise Criteria levels.[3]

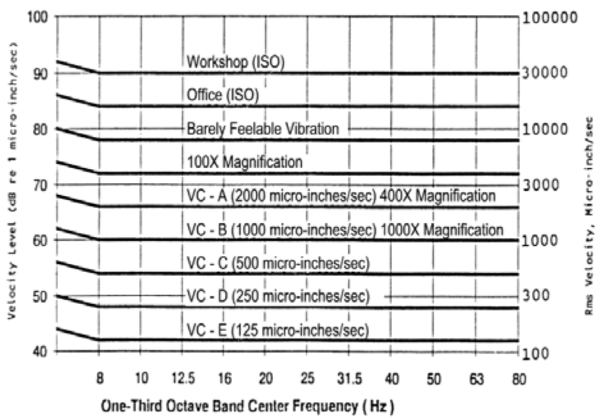

Figure 2. *Floor Criteria-Allowable Vibration*

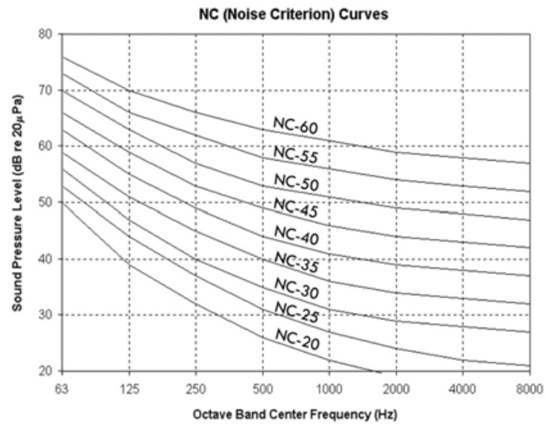

Figure 3. *Noise Criteria-Allowable Noise*

2. SITE CONDITIONS

2.1 Proposed Building and Existing Conditions

Vibration measurements were conducted in June 1998 to determine amplitudes of ground borne vibration at various locations on and around the site or the proposed ACES building. Existing ground borne vibration levels were shown to meet allowable criteria for the building, but there was concern that structural resonant amplification or addition of vibration from building systems might cause the new building floor vibration to exceed criteria, if not considered in design. Some measurements were made on the basement slabs-on-grade within a wing of an existing building that was to be demolished to accommodate the new building. Others were made on independent concrete paving outside the building, such as concrete pads and walkways on the ground surface. Seismic acceleration transducers with sensitivity 10 volts/g were used to assure flat response down to < 3 Hz, with low electronic noise. Vibration amplitudes below 16 Hz were inconsequential. Independent concrete pads on the ground exhibited strong peaks in 63 and 125 Hz 1/3 octaves and other notable vibration in 25 – 31 Hz range. The existing building basement slabs-on-grade showed greatest peak in the 63 Hz 1/3 octave, with amplitude approaching 60 dB.

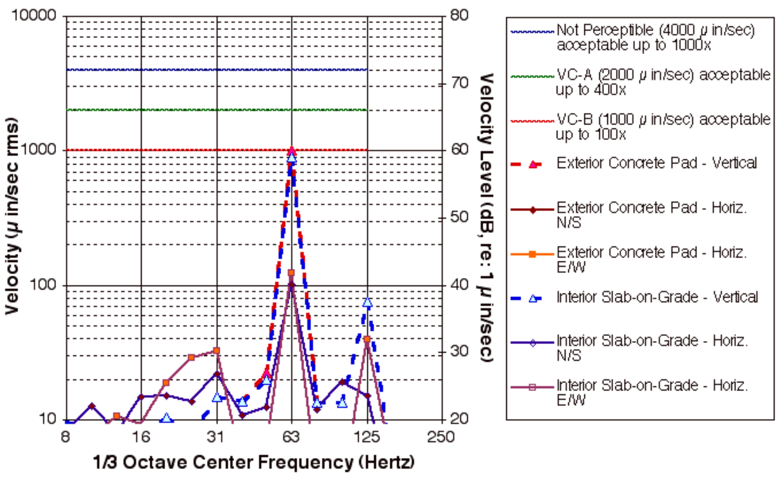

Figure 4. *Existing Ground Borne and Structure Borne Vibration (1998)*

3. DESIGN OBJECTIVES AND RECOMMENDATIONS

3.1 Design Building Structure to Minimize Response to Ground Borne Vibration

The first design objective was to mitigate known vibration disturbances from external sources, including the lower frequency disturbances in 25 – 31 Hz 1/3 octaves and the turbine and generator rotational frequencies: 60, 90, 180 and 240 Hz. External methods of isolating the building site, such as deep trenching in the limestone between the power plant and proposed building foundation were rejected due to expense, logistics and potential disruption to other nearby buildings on the campus.

The foundation was designed to reduce ground borne vibration transmission at the limestone to foundation interface and to damp vibration in the foundation slab. As vibration consultants, JEAcoustics recommended column footings on compacted sand fill and placement of compacted sand fill over the limestone before pouring the concrete foundation. Although compacted sand is a transmitter, its density is lower than that of limestone, so there would be some impedance mismatch at the stone-sand interface, resulting in partial reflection of vibration energy. The slabs-on-grade would also be damped by the contact, resulting in minimization of resonant vibration amplification in the slabs.

The building structure was designed with the intent to avoid allowing the frame's natural or resonant frequencies (and harmonics) to be coincident with the known ground borne disturbance frequencies. In addition, pipes and conduits coming into the building from below grade were recommended to have flexible connections at the building entrance to reduce transmission of the ground borne vibration.

3.2 Design Architectural Assemblies to Minimize Transmission and Radiation of Vibration

The second design objective was to isolate sensitive rooms from noise sources. For acoustically sensitive spaces requiring quiet background sound levels, including the Auditorium (speech with audio-visual presentation), Visualization Lab and Electronic Seminar (two-way interactive audio and video), JEA recommended to be designed with partitions and ceilings de-coupled from structural elements. Framing supports were placed on neoprene pads. Hanger and lateral braces for ceiling and wall support incorporated resilient vibration isolators.

3.3 Design Building Systems to Minimize Additional Vibration Input to Structure

The third design objective was to minimize additional vibration input from mechanical equipment, particularly at known external source disturbance frequencies. Disturbing frequencies from direct-coupled motors, compressors, fans and similar equipment are related to electric motor frequencies of 1750 rpm (29 Hz) and 3550 rpm (59 Hz), because the electrical power is 60 Hz in North America. Therefore, some reinforcement of the power plant vibration was unavoidable. It could be minimized with good vibration isolation of the equipment and attached pipes and conduits. Belt driven and variable frequency drive fans, however could be selected for operation at frequencies other than the known power plant vibration, and be designed with good vibration isolation of the fans, motors and attached conduits, pipes and ducts. Recommendations were made to coordinate equipment selections and operating parameters with structural design to avoid rotational frequencies that might be coincident with building resonant frequencies or their harmonics. Vibration isolators were sized for spring resonance generally 1/5 to 1/10 of equipment disturbing frequencies, depending on stiffness of floor location, to assure very low transmissibility through the isolators. Most building equipment was recommended to be installed on the basement slab-on-grade to take maximum advantage of slab damping, although some air handlers and smaller exhaust fans were located on column-supported floors and roof. Those installations on other than slab-on-grade were specified with softer (lower resonant frequency) vibration isolators, since column-supported floors are less rigid.

4. Implementation of Vibration Isolation Concepts

4.1 Structural Isolation and Damping

The vibration control recommendation to employ column footings on compacted sand conflicted with the geotechnical engineer’s recommendation to use drilled piers in the limestone. A compromise was reached to drill oversized piers to 75% of the pier depth and install caissons within them. The lower 25% of the piers would be in direct limestone contact. The upper 75% would have sand packed in the annular space between pier and limestone. Theoretically, the sand would provide reduction and damping of horizontal vibration in the foundation. The other foundation design recommendations were fully implemented, including compacted sand fill.

The building framing and column-supported floors were designed with consideration for known vibration disturbance frequencies. Vibration isolation of mechanical and electrical building equipment and attached conduits, ducts and conduits were coordinated with structural design.

4.2 Architectural Sound Isolation and De-coupling

Ceilings and partitions were detailed and installed with de-coupling techniques to reduce structure borne vibration transmission and re-radiation of noise. In addition, mechanical equipment rooms and chases were constructed with higher mass de-coupled partitions to isolate low frequency noise sources from sound sensitive spaces and to prevent air borne noise induced vibration in light weight structures.

4.3 Building Equipment Vibration Mitigation

Equipment selections were made to avoid coincident operating speeds (disturbing frequencies) with known external vibration sources. Vibration isolation was implemented to reduce transmission into the building structure. Sound attenuators were inserted into ducts and return air transfers to minimize low frequency mechanical noise transfer into occupied spaces.

5. VIBRATION AND LOW FREQUENCY NOISE CONTROL RESULTS

5.1 Initial Subjective Result

The ACES Building was completed and occupied in 2000. Vibration and noise control are successful. By subjective evaluation, occupants and users are satisfied with results. Visual images appear stabile on projection screens. Low frequency noise is contained at source locations and attenuated in ducts and equipment room wall penetrations. No post-construction corrections or modifications were requested for vibration or noise control. Noise and vibration performance validation measurements were not conducted.

5.2 Objective Measurement Results

JEAcoustics was asked to conduct new vibration measurements on the site in 2002 for a new project, providing an opportunity to obtain objective evaluation data on the ACES Building. Since 1988, there had been no change in the existing turbine-generator plant. In 2002, to evaluate a proposed 25 MW turbine-generator power plant expansion, the campus utility requested a baseline vibration survey to document existing ground borne vibration around the power plant and on floors of immediately adjacent buildings, including ACES. JEAcoustics returned to the site to conduct measurements. Where possible, the post-construction measurements were made near locations of pre-construction locations, and in a similar manner to obtain "before" and "after" comparative results. Due to the four-year lapse, with other changes on campus and variations in transient activity, some anomalies obscure the data comparisons.

Overall vibration levels are reduced. Peak vibration levels are reduced in horizontal, but similar in vertical. We believe that the drilled piers' lower 25% bearing on limestone result in more transmission of vertical vibration than desired. The upper 75% with compacted sand fill between limestone and piers appears to reduce transmission of horizontal vibration and/or damp resonant reaction in piers and foundation. Reduction in the pier to limestone bearing area would not significantly improve the result. A different kind of footing, bearing on an intermediate media between the footing and the limestone, could potentially improve vertical vibration mitigation.

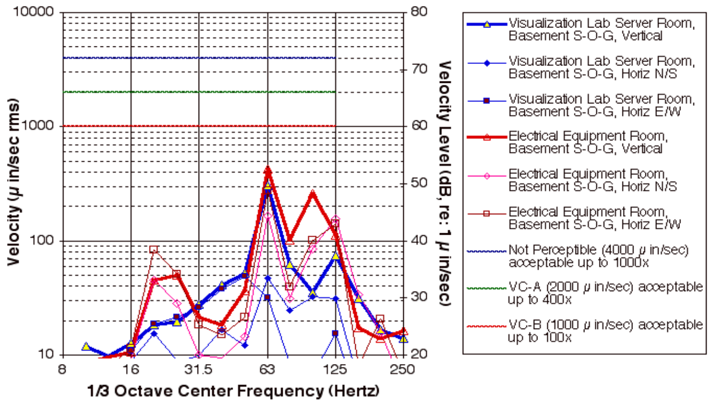

Figure 5. *Floor Vibration Results*

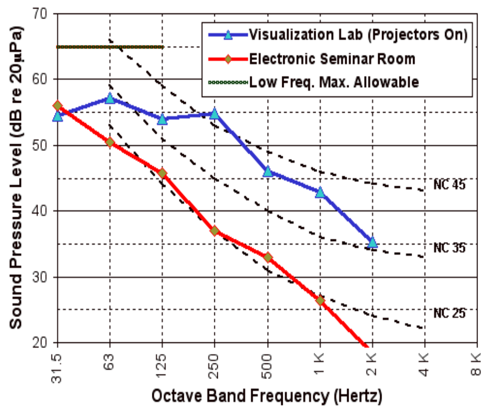

Figure 6. *Ambient Noise Results*

6. CONCLUSIONS

6.1 We believe that the drilled piers' partial direct bearing on limestone results in vibration coupling. Reduction in the pier to limestone bearing area would not significantly improve the result. A different kind of footing, bearing on an intermediate media between the footing and the limestone, could potentially improve vertical vibration mitigation.

6.2 Sound isolation and reduction of radiated noise due to structure borne vibration in partitions and suspended ceilings is successful. Low frequency noise is contained at source locations and does not induce vibration into lightweight structures. Pure tone radiated noise due to the ground borne turbine-generator vibration is not audible in sensitive rooms.

6.3 Assuring equipment disturbing frequencies to be non-coincident with external disturbing frequencies and providing vibration isolation of equipment and attached elements worked well to prevent increases to the known external vibration disturbance.

REFERENCES

[1] C. Gordon, "Generic Criteria for Vibration-Sensitive Equipment", in *Proceedings of International Society for Optical Engineering (SPIE),* San Jose, CA, 1991, pp. 71-85.

[2] American Society of Heating, Refrigerating, and Air Conditioning Engineers, Ch. 46: Sound and Vibration Control, ASHRAE, Atlanta, GA, 1995, pp. 46.22-46.25.

[3] L. Miller, Noise Control for Buildings and Manufacturing Plants, Ch. 3: Vibration Criteria, Bolt Beranek and Newman, Cambridge, MA, 1981, pg. 3-2.