Pneumatically Isolated Inertia Base with Active Damping
For a Transmission Electron Microscope (TEM)

Jack B. Evans, JEAcoustics - Engineered Vibration Acoustic & Noise Solutions
1705 W. Koenig Lane, Austin, Texas 78756 USA.
E-mail: Evans(at)JEAcoustics.com

Summary
Low frequency sound and vibration affects the performance and use of electron microscopes, by disturbing the stability and resolution of the specimen’s video image. A transmission electron microscope (TEM) addition was proposed to an existing research suite that had three scanning electron microscopes (SEM). The TEM, which is very heavy, rather tall and has a high center of gravity, is very sensitive to floor vibrations. This case study presents sources of disturbing vibration with spectrum measurements. The designs of the microscope room and an actively-damped, pneumatic vibration isolation system are discussed. Post-installation vibration measurement results to validate performance are presented in spectral analysis charts versus criteria. Drawings and photographs illustrate the installation.

Introduction
Electron microscopes use electron beams to “see” very fine microscopic detail. Scanning electron microscopes (SEM) project beams that trace back and forth over the surface of a specimen to create an image similar to a television picture. Transmission electron microscopes (TEM) are somewhat more sensitive to vibration than SEMs, because they hold an electron beam at a three-dimensional point within the specimen to create an analysis image. Loud low frequency airborne sound levels may induce vibration into lightweight structures, and building floor vibration may transmit to disturb SEMs and TEMs. In both cases, vibration may disturb the specimen or it may disturb the stage where the specimen is placed and/or it may cause differential movements between the beam projector and the specimen, resulting in image “jitter” (movement) or loss of image resolution (blur). It is necessary, therefore, to consider low frequency sound and vibration in the design of electron microscope installations.
A TEM addition was proposed in an existing SEM laboratory suite (see plan below). The facility was a basement level suite of rooms with slab-on-grade floors within a multistory research tower. An internal circulation corridor provided access to SEM rooms and a service corridor behind the rooms housed auxiliary support equipment. The existing SEMs had histories of occasional transient disturbances even though they were on spring isolated inertia bases. Vibration sources that could potentially disturb the electron microscopes included building systems such as HVAC and central plant equipment, the ancillary support equipment for the SEMs, footfall and rolling-wheel traffic in nearby corridors, and ground borne vibration from nearby roadway traffic or other building foundation emissions. Slab-on-grade floors are inherently damped due to their ground contact, so that footfall impacts and rolling wheels in corridors are of much less concern than they would be on suspended, or column-supported floors, which are not as well damped. Very low frequency ground borne disturbances, however, are transmitted through slabs-on-grade. Machine vibration can also be transmitted if those sources are not properly vibration isolated.

1.0 Establish Criteria and Design Parameters.

The research department of the institution had selected and purchased a TEM, of which the Facilities Department would manage the installation. The TEM’s manufacturer surveyed the proposed installation location relative to parameters for temperature, humidity, electro-magnetic interference, noise, vibration, etc. to determine acceptability of existing conditions, or identify deficiencies to be corrected in the installation design. Manufacturer’s proprietary criteria are not disclosed here.

Room Criteria (RC, see below) are used for allowable background noise due to building systems (not including noise generated by occupants or user-installations). In addition to a family of 5 dB/octave slope criterion lines, low frequency octaves are annotated for noise levels capable of inducing vibration into light-weight structures (regions “A” and “B” on chart below). The manufacturer’s allowable noise criterion was 60 dBC. RC-40, which acoustically sums to 39 (with C-weighting applied) was selected for the TEM room. Lower frequency airborne noise above Region “B” vibration inducing level was not permitted.

The TEM manufacturer’s allowable vibration criteria are expressed in narrow-band displacement, based on the TEM equipment sensitivities and performance aspects. Generic floor vibration criteria (see below) are in common use for structural design of buildings, expressed in RMS velocity terms over 1/3 octave bandwidths. Constant velocity with respect to frequency is used, whereas those amplitudes in acceleration or displacement would vary with frequency. Allowable floor vibration was established.
as 3 µm/sec (125 μ-in/sec) RMS velocity 8-100 Hz (constant acceleration below 8 Hz) for the project design, based on comparison with equipment criteria. To do this, the TEM manufacturer’s peak-to-peak narrow band vibration was summed into RMS 1/3 octaves and integrated from displacement to velocity to compare with the (dissimilar) generic floor criteria for best correlation.

1.1 Concept.

Vibration control theory and transmissibility via isolators is so widely known and understood, that it will not be discussed here, except to note the following, and to describe the applications for this project. Isolator resonant frequency, \( f_n \), should be lower than disturbing frequency, \( f_d \), to assure that no disturbance energy is in the amplification frequency range of the isolators. When the disturbing frequency, \( f_d \), is greater than \( \sqrt{2} \times \) spring frequency, \( f_n \), transmissibility (via the spring) is less than 1.0, or in other words, energy is attenuated. If the \( f_d \) is less than \( 1.4 \times f_n \), transmissibility is 1.0 or greater, meaning that the disturbance energy is amplified. Similarly, if isolators are in series, or one isolator is above another, and they have very similar resonant frequencies, their transmissibility curve “skirts” can combine, resulting in unwanted amplification or resonant reactions.
This electron microscope installation project involved broadband ground vibration with low enough frequencies that some isolator amplification could not be avoided, i.e., the disturbance frequency extended down to the isolator resonance frequency. In addition, the selected TEM is fabricated with medium-deflection spring isolators at the floor level (see TEM photo above), which are appropriate for normal building systems vibration disturbance frequencies, but not adequate for the very low frequency ground borne vibration found at this particular site. Therefore, isolators would be required with much lower resonant frequency than the TEM’s floor isolators. An inertia base was needed to lower center of gravity and to provide stability for a TEM vibration isolation system. To prevent spring-in-series amplification (re: overlapping transmissibility curves), the base isolator spring resonance could not be coincident with the TEM floor isolators. At the same time, the inertia base isolators would need resonant frequency as low as possible, preferably at 1 Hz or less to avoid amplification from the very low frequency ground energy. Ultimately, it was determined that damping would be necessary to suppress isolator resonance issues (reduce amplitude at spring resonance frequency, $f_n$).

1.2 Analysis Procedure and Instrumentation.

To determine vibration isolation parameters, it was necessary to determine external ground borne and internal building vibration amplitudes and spectra. In addition, ambient noise in the proposed TEM space and adjacent areas required evaluation to assure no induced vibration due to loud low frequency airborne sound.

A Larson-Davis Labs 2900 two-channel real-time spectrum analyzer was used with two Wilcoxn #731A seismic accelerometers with 10 V/g sensitivity, capable of sub-micron measurement from 1 Hz for ground borne and floor vibration measurements. Measurements were conducted for 30-120 seconds and data were acquired for $L_{min}$, equivalent level, $Leq$, and transient peak-hold, $L_{max}$. The $Leq$ is an integrated average that provides reliable indication of steady-state ambient conditions. Simultaneous measurements can be made in two directions at a single location, or at two separate locations, but 3-axis measurements ($x$, $y$, $z$ horizontal and vertical) cannot be accomplished, and therefore, may vary according to which/how many transients occurred during individual measurements. Pipe, duct, ceiling and partition surface measurements were made with the same analyzer, using a Wilcoxon #726 10 mV/g accelerometer. Airborne sound was measured with an ANSI Type I ($\pm 1$ dB) precision microphone and pre-amplifier, using the analyzer noted above.
2.0 Preliminary results.

Ground borne, floor and pipe vibrations and ambient background noise were measured in the existing facility for analysis, prior to initiating installation design.

2.1 Results of Original Site Characterization Measurements.

Ground borne vibration measurements were conducted outside the building to characterize external vibration sources. Structure borne vibration was measured on the existing slab-on-grade floors of the proposed TEM installation site and an existing SEM room to characterize building vibration conditions that resulted from the combination all sources (Leq = ambient; Lmax = disturbance, shown below with 3μ/sec velocity criterion). Vibration spectrum measurements on pipes and other elements in the ceiling plenum were made to identify discrete frequencies of building equipment sources or potential radiated noise. After comparisons with the TEM manufacturer’s allowable vibration criteria and the generic floor vibration criteria selected for building design, attenuation requirements were determined, based on difference between transient disturbance amplitudes and allowable vibration.

Ambient airborne noise spectra were acquired in the existing SEM rooms, in the ancillary equipment room, in the proposed TEM installation site (a conference room to be converted) and in an adjacent laboratory glass-wash facility, to characterize background noise conditions (shown above relative to RC-40). Measurement results would be used in architectural room design to determine partition and door sound transmission loss requirements and in and engineering to determine mechanical noise control parameters for TEM room air conditioning, exhaust systems and piping.
2.2 Findings and Recommendations.

Ambient (continuous) background noise from building systems was found to comply with manufacturers allowable 60 dBC sound criterion (equivalent to RC-40) in the existing conference room that was to be converted into a TEM room. Therefore, no corrections were necessary. Designs for HVAC and exhaust modifications to accommodate the TEM would need to consider noise to assure completed project compliance with noise criterion. Pipes in the ceiling plenum would need to be removed from the space or lagged (enclosed in a noise barrier jacket) to prevent radiated tonal noises. In addition, partitions and doors for the support equipment room and adjacent spaces would need to be designed to prevent noise intrusions.

Horizontal vibration measurement results were generally in compliance with manufacturer’s narrow band displacement criteria, except frequencies below 16 Hz.

Vertical ground borne and structure borne floor transient vibration disturbances exceeded manufacturer’s permissible vibration criteria at frequencies below 25 Hz. Continuous floor vibration was marginally in compliance with criteria. Based on measurement results, it was determined that very low frequency vibration isolation would be necessary for the TEM installation to prevent ground borne transient disturbances. In concept, a vibration isolated inertia base design was indicated, but, as noted above, the very low frequency ground vibration made practical applications difficult, so some method of damping was recommended (conceptually) to reduce isolator resonance problems. In addition to TEM isolation, building systems and TEM support equipment additions and modifications would require vibration isolation to prevent the increase continuous ambient building vibration beyond existing levels.

3.0 Implementation.

Architects and engineers were retained to design building modifications, including walls, ceilings, doors, HVAC, exhaust, lighting and TEM ancillary support equipment installations (in an adjacent room). Design measures for noise and vibration control were implemented to assure continuous background noise and transient noise intrusions into the TEM room would meet allowable noise criteria. The building noise and vibration controls were conventional in nature, so are not discussed in detail.

Consultation between the TEM manufacturer, the institution facility management, the research department and the vibration consultant resulted in a consensus agreement to retain a design-build contractor to implement the damped isolation and inertia base concept. The contractor chosen was an isolator manufacturer that specialized in pneumatic and active isolation systems for laboratory and cleanroom equipment. Because the TEM is tall and heavy, the contractor wanted to design a 10:1 ratio of inertia base mass to combined TEM and ancillary equipment masses (only those to be installed on the inertia base). Active isolation was considered, but the desired mass of the base could not be economically supported by active isolators. Pneumatic or air-spring isolators could feasibly support the inertia base and TEM, but to control potential resonance disturbances from transient ground disturbances, active vibration cancellation units were proposed to be installed in parallel with the air isolators, for the purpose of controlling vibration less than 3 Hz and resisting air isolator resonance problems. After review by the architect, structural and
mechanical engineers and the facility manager, the concept was accepted and an implementation plan, schedule and budget were developed.

3.1 TEM Room and Isolation System Design.

The TEM room was designed to be built with steel stud framed drywall, i.e. gypsum or plasterboard. Resilient mountings were recommended on one side of the partition framing to control transmission of impact and structure borne vibration. All partition penetrations, for ducts, pipes, conduits, and other services were specified to be sealed air-tight. The door between support equipment room, which would house moderately noisy and tonal transformer, compressor, vacuum pump and similar equipment, was specified to be a STC-42 sound rated frame and door assembly. Noise attenuators were specified in ducts that penetrated the TEM room partitions. For control of reverberant noise build-up, an NRC 0.80 ceiling was specified and NRC 0.80 acoustical panels were specified for wall areas above 1.5 m.

Fig. 13: Plan: TEM and Equipment Rooms. Note TEM’s 6 springs on isolated Inertia Base

Floor demolition and construction of a 1.4 m deep concrete pit was designed to accommodate the proposed inertia base, isolators and active dampers. The pit floor slab-on-grade was designed to be 0.4 m (16") thick to support the massive base & TEM concentrated loads (re: 10 isolator supports). The pit walls designed as below-ground retaining walls (re: hydrostatic pressure). A floor trench was designed to connect services between the support equipment room and the TEM as well as it’s isolation system components. Structural supports and an access tile floor was designed to span over the base for a walking surface around the TEM, so that researcher activities within the TEM room would not disturb the base.
The isolation system contractor selected large weight capacity isolators with nominal 1 Hz resonance, with active dampers (vibration cancellation) and controls for the TEM base. The vibration consultant and structural engineer designed the inertia base to achieve the desired mass within length, width and depth parameters allowed by the room and pit sizes. Combined weights of the TEM and ancillary equipment on the isolated base exceeds 6,000 Kg, so the base weight would approach 60,000 Kg. To maximize base mass within a limited volume, the base was designed as a segmented steel pan, to be filled with lead pellets, which have significantly greater mass than concrete, and covered in epoxy cement. Each side of the base would be supported by five pneumatic isolators, for a total of ten; each capable of supporting more than 6,000 Kg. Four active cancellation units would be placed at base corners.

Fig. 14: Section & Side Elevation Views: Inertia Base with Isolators & Active Dampers

3.2 Demolition, Construction and Installation.

A demolition and construction contractor was retained at the same time architects and engineers were, for the purpose of coordinating construction issues throughout design, and to minimize transition from design to construction phases. Demolition removed walls and the existing floor slab. The inertia base pit and services trench areas were excavated. The pit floor and retaining walls (below grade) were constructed. The structural steel segments of the inertia base were fabricated off-site in a way that they could be trucked to the building receiving dock and moved into the TEM room through building doors. The base segments were assembled within the pit, then filled with lead. The lead was vibrated to settle (minimize gaps), then covered with epoxy cement to have a solid top surface. A raised baseplate was installed in the area where the TEM supports would bear on the inertia base. The access floor structure and tiles were installed over the top of the inertia base, and surrounding, but not touching the base plate bearing area for the TEM.

Fig. 15: Base & Floor Structure Installations Fig. 16: Isolator and Damper Supporting Base
While the inertia base, services trench and access floor systems were installed, architectural construction, piping, ductwork and other building services were fabricated and installed. TEM support equipment with connected piping, conduits and cabling were installed in the support room. Then TEM components were delivered to the site, assembled and installed on the inertia base.

4.0 Final Results & Conclusion.

The TEM manufacturer assembled and installed the microscope and ancillary equipment. Post-installation performance measurements by installation/technical representatives indicated that electro-magnetic interference, temperature, humidity, noise and vibration conditions met the manufacturer’s minimum facility requirements.

Since the institutional researchers have had access to and use of the TEM, there have been no complaints about image stability or distortion due to facility conditions. The Facility Manager reports (subjective) performance satisfaction.

The vibration consultant recently returned to the site after some months of TEM use to conduct noise and vibration measurements in the facility. Measurements were conducted on the pit floor and the TEM concrete slab-on-grade room floor, to determine transmitted ground borne and structure borne building vibrations. Measurements were made on the base pit floor and several locations on and near the TEM, including top of the inertia base and the base plate under the TEM, to determine vibration reductions to those points from the base pit floor. The airborne sound spectrum measurements were made for comparison with noise criteria.
4.1 Post-Construction Performance Validation Measurements.

When making simultaneous two-channel measurements to determine differences, we mount both transducers on a common surface for measurement. Then, keeping the mounting as is, we exchange the signal cable inputs and re-measure. This provides confirmation that the transducers, cabling and analyzer are obtaining the same results. It is an unfortunate fact of life, but things sometimes go awry in the field. If we later find an incorrect setting or condition, the data can be corrected. Return to the site for new data is preferable, but not always possible.

Initial review of reduced data after returning from the site to our office did reveal that the second channel had an incorrect frequency span setting for the post-installation measurements, which had the effect of reducing measured amplitudes below 20 Hz. To make comparisons between simultaneously measured channel 1 and channel 2 data for this case-study, it was necessary to correct the channel 2 data, based on the comparative measurement procedure described in analysis procedures above. This study focuses on very low frequency conditions which unfortunately fall within the corrected frequency span. It is hoped that the site can be re-visited in the future to confirm the corrected data, but that could not be done in time for this manuscript.

The continuous background sound spectrum in the TEM room is within the marginal tolerances of RC-40 (+3 dB < 250 Hz, +2 > 250 Hz), and is below the “B” region for potential airborne induced vibration. This meets the manufacturer’s allowable overall 60 dBC noise criterion. The noise level in the TEM support equipment room exceeds RC-55, and has annoying tonal peaks, but due to effective partition and door seal designs, it is barely audible in the TEM room (spectra do not match).11

The simultaneous, 2-channel, 1/3 octave vibration spectra in dB, re: 1 μm/sec RMS, on the pit floor and on the top of the inertia base are shown on the left chart below compared with 3μ/sec RMS floor vibration criteria. The difference between pit floor and the top of TEM spring mount (on the inertia base) is shown on the right chart. The channel 2 receiver data are corrected for frequency response below 20 Hz.
4.2 Conclusion.

Active cancellation can provide very low vibration disturbance control ≤ 1Hz and damping of pneumatic isolators with low resonant frequency. Transient disturbances did not result in resonant reaction or isolator amplification, because they were controlled by the active damping.

The unusually large base and isolators used to compensate for the TEM’s high center of gravity were expensive. For future similar installations, a suspended “sling” or “cradle” configuration may be considered, where isolators are floor located alongside the isolated apparatus, and installed with height-saving brackets to suspend the apparatus below the tops of the isolators. Feasibility may be limited to lower weight systems, due to size, weight and rigidity requirements of the cradle.

Acknowledgements

The author wishes to express appreciation to Baylor College of Medicine, Houston, Texas for being included on the design team and for permitting post-installation access for performance validation measurements. In addition, the author acknowledges JEOL USA, Inc., Integrated Dynamics Engineering Inc. (IDE) and Wilson Architectural Group, Inc. for illustration images. Dan Kupersztoch of JEAcoustics provided data analysis of Jack Evans’ measurements and created illustration charts for this manuscript.
References

1. A.B. Alkek Bldg. Basement (S.W. corner), Reference Drawings, Baylor College of Medicine, Project Management, Houston, 6/2001
7. J. Evans, “Ground Borne (External) and Pipe Borne (Internal) Vibration Analyses,” JEAcoustics, June, 2004
8. IDE design-install Alternates Proposal for Baylor college of Medicine, Integrated Dynamics Engineering, Aug, 2004
9. Ibid. # 6, above and JEAcoustics design recommendations correspondence with Architect
11. JEAcoustics’ post-installation measurements, 20 July, 2006