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GROUND-BORNE NOISE AND VIBRATION CONTROL: A STATE-OF-THE-ART PERSPECTIVE

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INTRODUCTION

Practical vibration control provisions include ballast mats, resilient direct fixation fasteners, and floating slabs. Intense research is being conducted to refine prediction methods, develop lower cost vibration isolation alternatives, and improve performance. Some of these provisions and their performance characteristics are described below.

RESILIENT DIRECT FIXATION FASTENERS

The Los Angeles County Metropolitan Transit Authority (LACMTA) and the Washington Metropolitan Transit Area Transit Authority (WMATA) have each developed soft fasteners for reducing ground vibration at frequencies above about 30 Hz. The WMATA design is very similar to the Clouth "Cologne Egg, " and has a vertical stiffness of about 10MN/m. This fastener must pass a unique qualification test which includes measuring the transfer mechanical impedance over a frequency range of 10 to 500 Hz, using techniques developed for the NYCTA.[1] The LACMTA B616 soft fastener has the same anchor bolt pattern as the standard direct fixation fastener, and a static stiffness of about 10.5 MN/m, roughly 45% less than the standard A616 fastener. As a result, this fastener should produce about 5 dB lower groundborne noise level than the standard fastener at frequencies in excess of about 30 or 40 Hz, sufficient to avoid using floating slabs to control groundborne noise in marginal situations where perceptible vibration is not expected to be a problem.

BALLAST MATS

Two configurations of ballast mats have been proposed at the Portland Tri-Met for surface ballast-and-tie track. The resilient ballast mat and ballast form a spring-mass isolation system. The first configuration includes a concrete base and a Clouth Vibrex 1,000 mat consisting of inverted natural rubber cone springs placed on a concrete base or invert. The second, and less effective design, incorporates a homogeneous ballast mat such as provided by Phoenix or Getzner, placed directly on tamped soil or compacted sub-ballast. Conventional installations of ballast mats in Europe are in subway with concrete base, for which vibration insertion losses are predicted to be relatively high.[2] For surface track , the shear modulus of the soil may give a support modulus comparable to that of the ballast mat, and thus render the ballast mat ineffective.

Ballast mat performance for surface track is predicted with the model described in Figure 1. The model represents the rails, ballast, and concrete base or sub-ballast, as continuous beams. The ballast mat and soil are represented as locally reacting springs and dashpots. The soil/foundation model is derived from lumped parameter models of foundations on elastic half-spaces.[3,4] The soil is assumed to have a shear wave velocity of about 180 to 240 m/s. The real part of the soil input impedance is due to vibration power radiation (geometric damping). A vibratory point load acts at the rail head, and the calculation of insertion loss is based on the reduction vibratory power radiated into the surrounding soil. The results of this calculation are presented in Figure 2. The Clouth Vibrex mat on concrete base is predicted to provide about 12 dB vibration reduction relative to standard ballast-and-tie track. The uniform mat on bare soil or compacted subgrade is projected to provide about 9 dB vibration reduction relative to standard ballast and tie track. The vibration reductions are limited to the frequency range in excess of about 30 Hz. In both cases, little vibration reduction is predicted at frequencies below about 25 Hz, though the concrete based ballast mat appears to be slightly more effective than the soil based mat. Figure 2 also illustrates measured ballast mat performance data obtained at San Francisco Municipal Railway for a Clouth Vibrex 1000 mat on concrete base embedded in the soil surface at grade. These results indicate that the predicted vibration reductions are consistent with measurement data.

FLOATING SLAB TRACK

Floating slab track vibration isolation with resonance frequencies at about 8 Hz have been incorporated into new track construction at the San Francisco Bay Area Transit District (BART), and the Metropolitan Atlanta Regional Transit Authority (MARTA), utilizing a double-tie design originally developed for the Toronto Transit Commission (TTC), to control vibration at frequencies above 12.5 Hz. The BART design was driven by the need to isolate surface track to protect nearby residential structures from perceptible vibration in the 12 to 20 Hz frequency range. Part of the projected impact is due to particularly soft soils, and is based on propagation tests conducted according to procedures developed for the U.S. Department of Transportation.[5] A unique feature of the BART design is the use of high density concrete, which reduces the overall thickness of the slab to about 14 inches. The MARTA design was developed to control groundborne and structure-borne vibration in a hospital proposed to be built directly over the subway box structure after construction of the subway. The vibration levels expected are based on several measurements of subway bench vibration at various locations on the MARTA system, and application of a projected vibration insertion loss for the floating slab isolation system. Figure 3 illustrates the 8 Hz MARTA floating slab design, which incorporates a 2 foot thick concrete double tie slab of mass 6,800 Kg. The normal operating configuration includes 4 natural rubber isolators. Additional isolators can be incorporated to increase stiffness at transition regions between unisolated and isolated track. The main support pad for the MARTA 8Hz floating slab shown in Figure 3 was designed to provide low shear strain and control lateral slip between the bearing surface of the pad and concrete surfaces. Lateral slip is further reduced by gluing the pads to the concrete surfaces. Pad thickness was about 0.1 m, with an overall dimension of 0.4 m.

The main support pads of all discontinuous floating slabs used in the United States are manufactured from natural rubber, using a formulation originally developed for the TTC double tie support pads used on the Spadina Line. The formulation exhibits low creep, and results in high reliability and dimensional stability. Synthetic rubber formulations exhibit higher creep rates than natural rubber formulations. Many of the original WMATA floating slab pads were manufactured from a urethane product which absorbed water in such amounts as to destroy them, necessitating their replacement. Had natural rubber pads been used as originally designed, no failure of the pads would be expected, as indicated by successful installations at Toronto, MARTA, and BRRT. Natural rubber pads are reliable, exhibit very low creep rates, are not subject to corrosion, and provide natural damping which controls the amplification of vibration at resonance. Their use results in a virtually maintenance free vibration isolation system. Finally, a particular advantage of the discontinuous pre-cast floating slab is that they may be installed by fork lift and positioned with air jacks, as was done at the TTC for the standard weight floating slabs, and also at the MARTA system for the 6,800 Kg slabs.

RAIL STRAIGHTNESS

Rail straightness is critical in controlling low frequency ground vibration in sensitive areas. Ground vibration frequencies have been related to the manufacturer's roller straightener pitch diameter.[6] More recently, vibration was generated at residential structures near a railroad in Kamloops as a result of replacement of "gag-press" straightened rail with roller straightened rail containing excessive vertical undulation.[7] Figure 4 presents 1/3 octave band vibration velocity data collected at 60 m from a double track alignment, one with roller straightened rail and the other with original gag-pressed rail. Community reaction may be expected when the velocity level exceeds about 85 dB relative to 10^{-8}m/s, as was the case in the present example. Narrowband analyses of the wayside ground vibration data identified a linear relation between frequency peaks and train speed, and these peaks were identified with the roller straightener pitch diameter. Subsequent measurements of rail profile with a laser interferometer verified the conclusions reached from the vibration data. The roller straightened rail was replaced with new rail roller straightened to British Rail standards for straightness. Repeat measurements indicated a substantial reduction of ground vibration, even though the effects of the roller straightener pitch diameter were still identifiable in the wayside ground vibration spectra.

This experience has motivated the recommendation of "super-straight" rail for sensitive areas where floating slabs are not practical for reasons of cost or construction limitations, or where additional vibration reduction is required at low frequencies. Examples may include alignments adjacent to semi-conductor manufacturers, or surface track alignments passing very close to sensitive receivers in areas of very soft soil. The MARTA 8Hz floating slab provision beneath the proposed hospital discussed above, was accompanied by a provision for rail straightened to European standards for high speed rail.

PRIMARY SUSPENSION

Figure 5 illustrates ground vibration levels for the Chicago CTA 2400 Series vehicle with a Wegmann design bogie compared with ground vibration produced by the 2000 and 2200 series vehicles with LFM-CTA-1 and Budd Pioneer III bogies, respectively. For all train speeds considered, the Wegmann design bogie of the 2400 Series vehicle produced lower levels of vibration than the original older CTA 2000, and 2200 series vehicles at frequencies above about 16 Hz. The Wegmann design bogie incorporates a soft primary suspension system with special rubber springs in the journal area and a combination spring and rubber secondary suspension. Figure 6 illustrates the vibration reduction achieved by drilling holes in the rubber journal elastomer springs of the MARTA C-Car. The tests were conducted at the Transportation Test Center in Pueblo, Colorado. The original static and dynamic stiffnesses were calculated to be 31.5 MN/m and 63 Mn/m, respectively, and the static and dynamic stiffnesses of the modified suspension were calculated to be 7.9 MN/m and 15.8 MN/m, respectively. The reduction was on the order of 5 dB over a limited frequency range. The LACMTA Red Line vehicles were specified to have a primary suspension resonance frequency of about 12 Hz or less, which was actually achieved with chevron suspensions, giving an actual vertical primary suspension resonance frequency of about 8 to 10 Hz. This specification was a direct attempt to control ground vibration at the source; the vehicle. To date, no complaints have been received concerning groundborne noise and vibration on the Metro Red Line.

CONCLUSION

The provisions described above are in addition to now accepted methods such as rail grinding, wheel truing, slip-slide control, continuous welded rail. Other methods may be explored, such as lowering subway depth, increasing subway invert mass, and soil treatment.

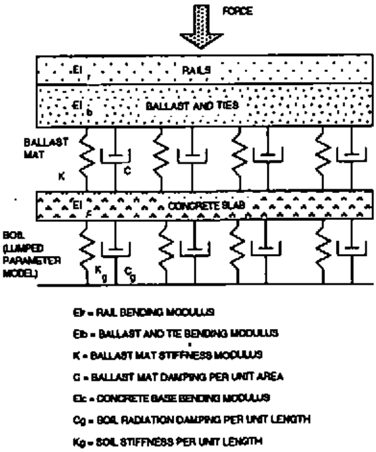

FIGURE 1 LUMPED PARAMETER MODEL OF BALLAST MAT VIBRATION ISOLATION SYSTEM FOR SURFACE TRACK

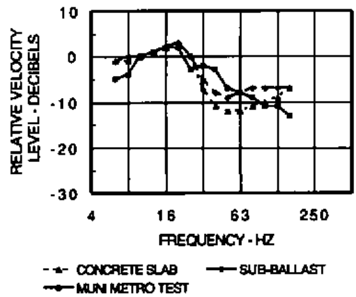

FIGURE 2 PREDICTED AND MEASURED BALLAST MAT PERFORMANCE

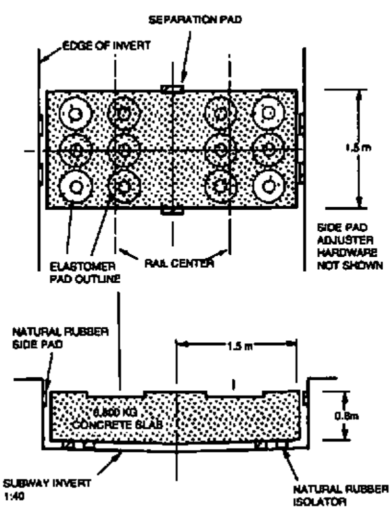

FIGURE 3 PLAN AND ELEVATION OF 8HZ RESONANCE FREQUENCY FLOATING SLAB VIBRATION ISOLATION SYSTEM

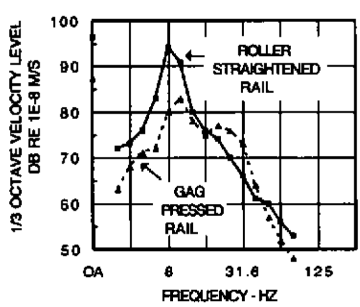

FIGURE 4 GROUND VIBRATION AT 60 M FROM COAL HOPPER CARS TRAVELING AT 45 MPH ON ROLLER STRAIGHTENED AND GAG PRESSED RAIL.

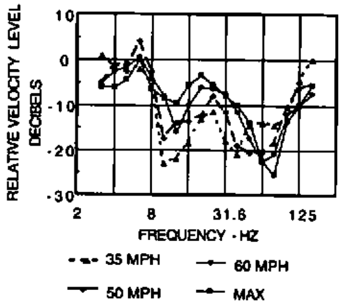

FIGURE 5 GROUND VIBRATION OF CTA SERIES 2400 VEHICLES WITH WEGMANN BOGIES RELATIVE TO 2000 AND 2200 SERIES VEHICLES

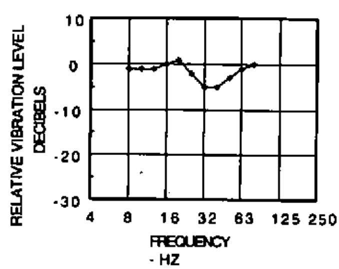

FIGURE 6 GROUND VIBRATION OF SOFT MODIFIED PRIMARY SUSPENSION OF MARTA C-CAR RELATIVE TO UNMODIFIED CAR

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