Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Journal of Sound and Vibration 293 (2006) 873–877
JOURNAL OF SOUND AND VIBRATION
www.elsevier.com/locate/jsvi

Performance of ballast mats on passenger railroads: Measurement vs. projections

C.E. Hanson[a,*], H.L. Singleton Jr.[b]

[a]Harris Miller Miller & Hanson Inc., Burlington, MA 01803, USA
[b]Cross-Spectrum Labs, Springfield, MA 01139, USA

Accepted 26 August 2005
Available online 7 February 2006

Abstract

Ballast mats have been installed on urban railway systems throughout the world to provide isolation of ground-borne vibrations from trains. In general, the performance has been found to be satisfactory. However, often there is a variance between the claims of the suppliers of ballast mats and the actual performance of the product in the real world. The classic case involves an infinite terminal impedance applicable to a tunnel configuration. However, a ballast mat installation outdoors on surface track with sub-grade slabs may not have the same performance as a tunnel base where sides are stiffened by walls. In order to represent this situation, Kimura developed a simplified prediction procedure based on an original Wettschureck/Kurze model, with a finite termination impedance based on a flat beam model. This prediction procedure has been tested against measurements on at-grade installations on light rail transit and commuter railway installations in Baltimore and Boston. In both cases, the model showed good agreement with measured values for the resonant frequency dip and the mid-frequency insertion loss. At higher frequencies, however, the model over-predicted the insertion loss, as do many of the models used by ballast mat suppliers. Suggestions are made to account for the discrepancies between predicted and measured values.

1. Introduction

A theoretical impedance model was developed by Wettschureck and Kurze [1] for ground-borne vibration insertion loss characteristics of a tunnel invert in comparison with tracks at-grade using an elastic half-space as the terminal impedance. The model was applied to estimate the insertion loss of ballast mats in tunnels with an assumed infinite termination impedance as would be found in railway tunnels, bridges and ballastless track [2]. Wettschurek [3] went on to combine the two cases for applications to track at-grade by developing a finite impedance model based on an elastic half-space. This model is used to estimate the performance of ballast mats at grade. Prior to the publication of Wettschureck's modification, Kimura [4] used the finite impedance of an infinitely long thin beam in the Wettschureck/Kurze model to represent the case of a ballast mat installed on a relatively thin concrete or asphalt slab. This prediction procedure has been tested against measurements on at-grade installations at light- and heavy-railway systems in Baltimore and Boston.

*Corresponding author. Tel.: +1 781 229 0707; fax: +1 781 229 7939.
E-mail addresses: chanson@hmmh.com (C.E. Hanson), hls@cross-spectrum.com (H.L. Singleton Jr.).

0022-460X/$ - see front matter
doi:10.1016/j.jsv.2005.08.052

2. Original ballast mat model

The ballast mat model is schematically illustrated in Fig. 1. The components of the dynamic system consist of the vehicle, track, tie (sleeper), ballast, ballast mat and support slab. The simple one-dimensional, single degree-of-freedom model determines an insertion loss from the response of lumped mechanical impedances of the various components of the system during a train passage.

The "Source Impedance" (Z_i) looking upwards from the top of the ballast mat includes a mass term (the unsprung mass of the vehicle, the rail, tie and ballast) and a spring term (ballast dynamic stiffness). The "Ballast Mat Impedance" (Z_M) has its own dynamic stiffness and damping. The "Terminal Impedance" (Z_T) was originally assumed to be equivalent to a very stiff spring in the Wettschureck–Kurze model because it was developed for ballast mats in tunnels. For the at-grade configuration, Kimura assumed Z_T to be the beam impedance of a supporting slab with specific thickness and material properties. For purposes of this paper, Kimura's flat-beam model will be referred to as "the model."

The equation describing the insertion loss in decibels for the lumped-parameter model in Fig. 1 is

$$\Delta L = 20\ \log\left[1 + \frac{1/Z_M}{1/Z_i + 1/Z_T}\right]. \tag{1}$$

The key lumped parameters are as follows:

Source Impedance (Z_i), includes the unsprung mass (M) on the ballast stiffness (s_s) modelled as a simple spring–mass system:

$$Z_i = \{(\mathrm{j}\omega/s_s)[1-(\omega_o/\omega)^2]\}^{-1}, \tag{2}$$

where ω is the frequency in radians/second, $\omega_o = (s_s/M)^{1/2}$ is the resonance frequency in radians per second, and j is the imaginary unit.

Ballast Mat Impedance (Z_M), includes the dynamic stiffness and damping factor:

$$Z_M = C_M A_e(1+\mathrm{j}\eta)/\mathrm{j}\omega, \tag{3}$$

where C_M is the dynamic stiffness of ballast mat per unit area, A_e is the effective area of the ballast assuming conical load distribution, and η is the ballast mat damping loss factor. The effective area of the ballast is determined geometrically, including the ballast depth, width of tie, effective tie load distribution length per rail and load distribution angle.

Terminal Impedance (Z_T), modelled as the driving point impedance of an infinitely long thin flat beam corresponding to the material of the support slab:

$$Z_T = 2\rho\, c_p\, w\, t(1+j), \tag{4}$$

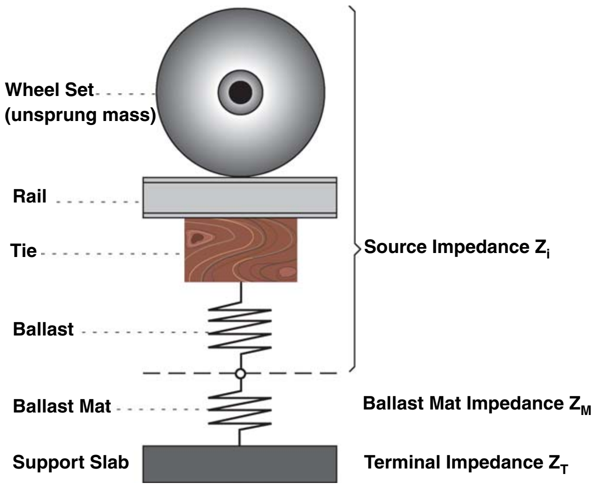

Fig. 1. Lumped parameter ballast mat model.

where ρ is the mass density of the slab, c_p is the bending wave speed in an infinite plate of thickness t, w is the width of the support slab, and t is the thickness of the support slab.

3. Comparison with measured results

The model was applied to two at-grade ballast mat installations in the United States where measurements of insertion loss were taken. The measured insertion loss data were obtained through wayside vibration measurements. Accelerometers were attached to steel stakes driven into the ground at positions equidistant from the centrelines of continuous track segments with and without ballast mats. The two track segments were typically within 100 m at locations where the soil conditions were similar at each accelerometer position. Train speeds were measured with a radar speed detector to allow for corrections resulting from speed differences. The differences in the measured vibration spectra between each corresponding accelerometer location were assumed to be caused by the presence of the ballast mat.

The vibration spectra measured at the ballast mat track sections were subtracted from those measured at the track segments without ballast mats to obtain the insertion loss results. The insertion loss measured at various distances were averaged together to develop an overall estimate of the ballast mat insertion loss.

3.1. Baltimore light rail transit study

The Baltimore Central Light Rail Line was the subject of a study of the effectiveness of a ballast mat. A short segment of this line was constructed with a profiled ballast mat installed outdoors at-grade on a concrete pad of 0.15 m thickness. The profiled mat is one with ridges or pyramids facing the slab to allow for controlled compression as the train passes. Parameters of the ballast mat, along with dimensions of the trackbed and unsprung weight of the vehicle, were obtained from the manufacturer and transit agency. These data, shown in Table 1, were used to calculate the insertion loss. Predicted and measured results are shown in Fig. 2.

3.2. Boston commuter railroad study

The subject of another study was a heavy rail system near Boston, Massachusetts. Several track segments were installed with profiled ballast mats. The insertion loss of a ballast mat at an outdoor, at-grade installation was measured and compared with predictions using the model. In this case, 10-car trains were pulled by heavy diesel-electric locomotives and the support slab was an asphalt layer of 0.15 m thickness. The parameters of the locomotive and track support system are also shown in Table 1. The results of inserting the relevant parameters into the model are shown in Fig. 3.

Table 1
List of ballast mat model inputs for Baltimore Central light rail transit study and MBTA commuter rail study

Parameter	Baltimore inputs	MBTA inputs
Type	Baltimore LRT vehicle	MBTA commuter locomotive
Unsprung mass of wheelset	1540 kg	3000 kg
Young's modulus for base plate material	$1.22\times10^{9}\,\mathrm{N/m^2}$ (concrete)	$1.22\times10^{7}\,\mathrm{N/m^2}$ (asphalt)
Poisson's ratio for reinforced concrete/asphalt plate	0.3	0.3
Mass density of base plate	$3\times10^{3}\,\mathrm{kg/m^2}$ (reinforced concrete)	$3\times10^{3}\,\mathrm{kg/m^2}$ (asphalt)
Dynamic stiffness of ballast mat	$0.014\,\mathrm{N/mm^3}$	$0.014\,\mathrm{N/mm^3}$
Loss factor of ballast mat	0.068	0.068
Ballast depth	0.33 m	0.33 m
Width of tie	0.25 m	0.25 m
Effective tie load distribution length per rail	0.5 m	0.5 m
Load distribution angle	60 degrees	60 degrees
Ballast stiffness	$5\times10^{8}\times(1+0.5\mathrm{j})\,\mathrm{N/m}$	$5\times10^{8}\times(1+0.5\mathrm{j})\,\mathrm{N/m}$
Thickness of track support plate	0.152 m	0.152 m
Width of track support plate	6.55 m	6.55 m

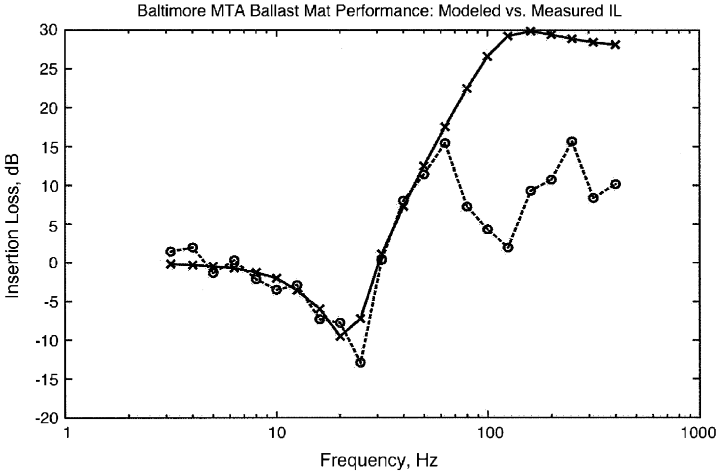

Fig. 2. At-grade ballast mat predictions vs. measured insertion loss on a light rail transit system; support slab is concrete with thickness 0.152 m. , modeled ballast mat insertion loss; and , measured ballast mat insertion loss.

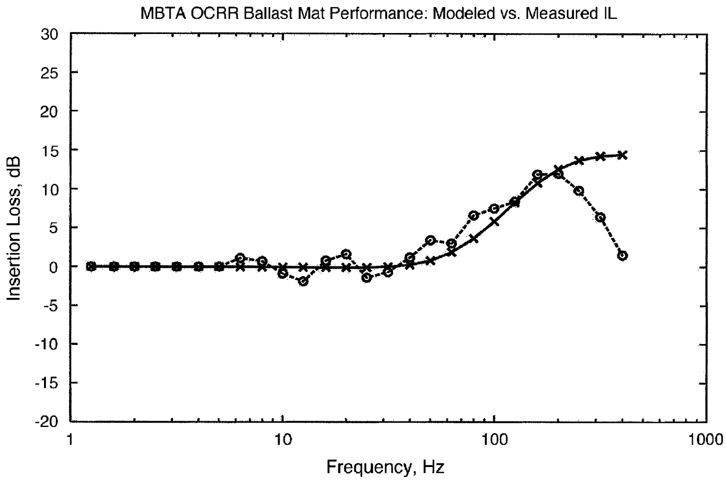

Fig. 3. At-grade ballast mat predictions vs. measured insertion loss on a commuter railroad; support slab is 0.152 m thick asphalt. , modeled ballast mat insertion loss; and , measured ballast mat insertion loss.

4. Discussion of results

Comparison of the predictions and the measurements indicates good agreement at frequencies from below the first resonance to approaching the frequency where a ballast mat provides its maximum insertion loss. The model successfully predicts the negative insertion loss at resonance in the case of the light rail vehicle. In both cases, the model gives a good indication of the frequencies where the ballast mat begins to become effective. It is remarkable that such a simple model can provide valuable information over a large range of frequencies. However, the model does over-predict the performance at frequencies higher than the predicted wheelset/ballast resonance frequency by a considerable margin in both cases. Among the reasons for over-prediction may be: measurement anomalies which may occur above 100 Hz due to the accelerometer mounting methods; cross modes of the slab; damping effect of the subgrade. Fortunately, the higher frequencies generally do not propagate through the soil efficiently. However, there are cases where ground-borne noise may be of serious concern—e.g., concert halls—such that the insertion loss at frequencies above 80 Hz is important. A more complete model may be able to correct this high-frequency deficiency.

4.1. Recommended improvements

This model is a simple, single degree-of-freedom system. The shapes of the measured insertion loss curves imply that a multiple degree-of-freedom system, with higher order resonances, may be more appropriate. In addition, the model could benefit from an improved expression of the driving point impedance of a plate on an elastic half-space with damping and transverse waves propagating into the ground.

Acknowledgments

The authors recognize the importance of the initial model development by Kurze and Wettschurek and the modifications by Kimura resulting in the HMMH model.

References

[1] R. Wettschureck, U.J. Kurze, Erschütterungen in der Umgebung von flach liegenden Eisenbahntunneln im Vergleich mit freien Strecken, *Acustica* 58 (1985) 170–176.
[2] R. Wettschureck, U.J. Kurze, Einfugungsdammass von Unterschottermatten, *Acustica* 58 (1985) 177–182.
[3] R. Wettschureck, Measures to reduce structure-borne noise emissions induced by above-ground, open railway lines, *Rail Engineering International* 1 (1997) 12–16.
[4] Y. Kimura, Control of ground-borne vibration from at-grade track using ballast mats, unpublished paper presented at the *1995 American Public Transit Association Rapid Transit Conference*, June 1995.