The prediction of vibrations from underground railway traffic based on wavelet analysis

ZHI-GANG YIN,JIN-MIN DING

School of Civil and Architectures of Tongji University, Shanghai200092, CHINA

Abstract: - In this paper, the vibrations environments induced by underground railway traffic were studied through the method of wavelet analysis with dynamic FEM. The accelerations measured on track are decomposed by the wavelet packet. The decomposed acceleration signals are applied as an excitation on tunnel invert. An invariant concrete tunnel, embedded in a homogeneous full space is analyzed using a pipe-in-pipe model. The free field response duo to an excitation in the tunnel is predicted and results obtained are compared to results measured. From the numerical investigation, the vibration intensities of the tunnels and nearby ground can be evaluated for the subway running.

Key-words: - Wavelet analysis; vibration; pipe-in-pipe model; dynamic FEM

1 Introduction

Ground-born vibrations induced by underground railways are a major environmental concern in urban areas. These vibrations propagate through the tunnel and surrounding soil into nearby buildings causing annoyance to people. Vibration is perceived directly or it is sensed indirectly as re-radiated noise. The frequency range of interest for subway-induced vibration is 1-80HZ and for the re-radiation noise it is 1-200HZ [1].

Dynamic loads of subway track are affected by lots of uncertain factor(such as: Vehicle ride, rail corrugation rate, sleeper cracking, rail fatigue, ballast degradation and other track-related phenomena) [2,3]. The dynamic response of tunnel-soil induced subway track is random process. The random process cannot be reflected by certain function. The vibration induced by train produce a wide range of frequency components. Previous studies on the problem are formulated in the time or frequency domain using a Fourier transformation. The basis functions used in Fourier analysis .The conventional Fourier analysis is not capable of describing the evolution of the spectral features of a signal as this evolves in time. Although the short-time Fourier Transform (STFT) which windows the input signal overcomes the time location problem to a large extent, it does not provide multiple resolution in time and frequency because the window is fixed. As the frequency is increased, there are more and more cycles within the windows Thus, individual frequency components are not treated in the same way. Wavelets, however, can be chosen with very desirable frequency and time characteristic as compared to Fourier techniques. In contrast to the STFT, which uses a single analysis window, the wavelet transform uses short windows at high frequencies and long windows at low frequencies. Thus the windowing of wavelet transform is adjusted automatically for low or high frequencies and each frequency component gets treated in the same manner without any reinterpretation of the results.

The aim of this paper is to investigate the application of wavelets in ground-born vibrations induced by underground railways the accelerations measured on track are decomposed by discrete wavelet packet transform (DWPT). The decomposed acceleration signals are regarded as loads acting on track. The time-response laws of tunnel-soil are obtained by dynamic FEM analysis. The results are significant for environmental evaluation.

2 Wavelet analysis and dynamic FEM analysis

The equation of motion for the system of tunnel-soil is given by [4]

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=-[M]\{I\}a_0(t) \quad (1)$$

where $[M]$, $[C]$, $[K]$ is mass ,damping, stiffness matrices respectively, $\{I\}$ is a $N \times N$ unite matrix, $\{u\}$, $\{\dot{u}\}$, $\{\ddot{u}\}$ is the vector of the displacements, velocities, acceleration of the system respectively, $a_0(t)$ is the vector of the accelerations measured at rail , and N is the number of degree of freedom of tunnel-soil.

Assuming the damping of the system is viscous damping. The N degree of freedom damped eigenproblem followed by the modal coordinate transformation, which must be done before the individual modal response can be evaluated. Uncoupled equation can be obtained by

$$\{x(t)\} = \sum_{i=1}^{N} \{\Phi^{(i)}\}\eta_i(t) \tag{2}$$

In which $\{\Phi^{(i)}\}$ is i th mode shape matrix. substituting(2)into(1),it is easy to show that

$$\ddot{\eta}_i + 2\xi_i\omega_i\dot{\eta}_i + \omega_i^2\eta_i = a_i a_0(t)$$
$$(i = 1,2,\cdots,N) \tag{3}$$

Where ξ_i is i th damping ratios ω_i is i th undamped natural circular frequencies $a_i = \{\Phi^{(i)}\}^T [M][I]$.

If we have zero initial conditions Eq(3)becomes

$$\eta_i(t) = \frac{1}{\omega_{di}} \int_0^\infty a_i a_0(t) e^{-\xi_i\omega_i(t-\tau)} \sin\omega_{di}(t-\tau)d\tau \tag{4}$$

Where $\omega_{di} = \omega_i(1-\xi_i^2)^{1/2}$ are damped natural circular frequencies of the system.

The measured acceleration is represented by the Haar wavelet basis function through the wavelet transformation. The WPT component function of the measured acceleration $a_0(t)$, i.e., $a_j^i(t)$ can be reconstructed from the wavelet packet coefficients as,

$$a_j^i(t) = \sum_{k=-\infty}^{+\infty} c_{j,k}^i \psi_{j,k}^i(t) = r_j^i c_j^i = r_j^i d_j^i a_0(t)$$

(5)

Where $r_j^i = [\psi_{j,0}^i, \psi_{j,1}^i, \cdots, \psi_{j,l}^i]$ $(l = 0,1,\cdots, N/_{2^{J-1}})$

$$d_{j+1}^{2i} = h^{j+1}d_j^i, d_{j+1}^{2i+1} = g^{j+1}d_j^i, d_1^0 = h^1, d_1^1 = g^1$$

h^{j+1}, g^{j+1} are matrices formed by the low-pass filter function and high-pass filter respectively. c_j^i is the wavelet packet coefficients for the acceleration with $c_j^i = d_j^i a_0(t)$

From the equation(4),the modal displacement of the i th degree of freedom can be obtained

$$\eta_i^j(t) = \frac{1}{\omega_{di}} \int_0^\infty a_i a_j(t) e^{-\xi_i\omega_i(t-\tau)} \sin\omega_{di}(t-\tau)d\tau \tag{6}$$

The response of the system is given by

$$\{x^j(t)\} = \sum_{i=1}^{N} \{\Phi^{(i)}\}\eta_i^j(t) \tag{7}$$

3 The pipe-in-pipe model

The pipe-in-pipe model is developed by Forrest and Hunt [5],Hussein [6] and Hussein and Hunt [7].The tunnel and the surrounding soil are modeled as concentric thick cylindrical shells. A track is modeled as an Euler-Bernoulli beam and is coupled to the tunnel wall.

3.1 Dynamic tunnel-soil interaction

A tunnel wall embedded within a continue of soil is formulated using a model of two concentric pipes known as tunnel wall, while the outer pipe represents the surrounding soil with an inner radius equal to the outer radius of the tunnel and an outer radius of infinite extent (Fig1). The two pipes are invariant in the longitudinal and satisfy the equilibrium and compatibility conditions at the tunnel-soil interface

4 Numerical example

4.1 Problem outline

An invariant tunnel is considered, embedded in homogeneous soil that is modeled as a full space without the presence of a free surface

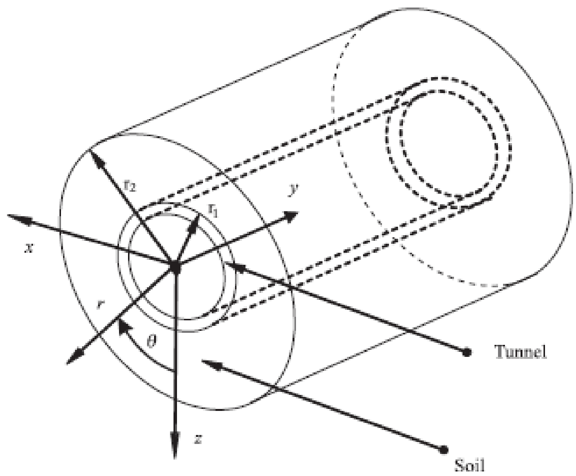

Figure.1.The tunnel wall, modeled as a thick cylindrical shell with outer radius r_1, is coupled to a continuum of soil with a cylindrical cavity.

The tunnel has an internal radius r_i =2.75m and a wall thickness. t =0.25m Hence, the outer radius of the tunnel or the radius of the cavity r_e is equal to 3.0m. The tunnel is made of concrete with a Young's modulus E_t=50×10^{9}Pa.

4.2 The accelerations measured

Use the accelerations [8](Fig2) measured on track are decomposed by the wavelet packet toolbox of Matlab. The decomposed acceleration signals are applied as an excitation on tunnel invert.

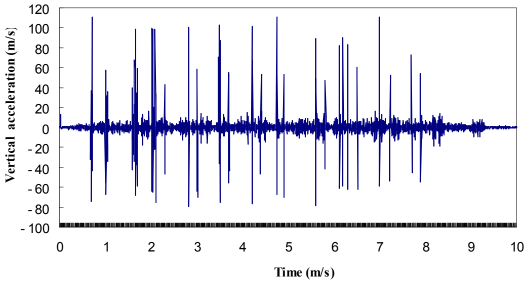

Figure.2 Time history curve of vertical acceleration for track

4.3 The response of the soil on surface

The response of the soil on surface is considered in the frequency range between 1 and 80Hz for the decomposed acceleration signals are applied on the tunnel invert.

Fig.3 shows the vertical acceleration of soil on surface. It has been shown that, the maximal divergence is 12 percent the result of calculation comparing to acceleration measured.

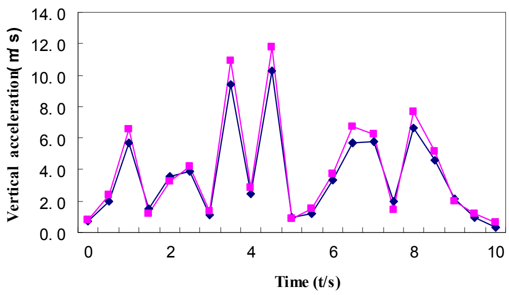

Figure.3. The dynamic response of soil

5 Conclusions

The main objective of the work presented in this paper is to use DWPT for estimating vibrations of the tunnel-soil system due to underground railway traffic. An invariant tunnel, embedded in a homogeneous full space is analyzed using pipe-pipe model. The study prospers a better understanding of vibrations from underground railways.

A numerical example has been used to demonstrate the use of the methods. The response of soil has been calculated It has been shown that, the maximal divergence is 11.1 percent the result of calculation comparing to acceleration measured. The prediction of vibrations from underground railway traffic based on wavelet analysis give a good match of the response measured on surface.

References:

[1] S. Gupta, M.FM.A comparison of two numerical models for the prediction of vibrations from underground railway traffic, *Soil Dyn Earthquake Eng*, Vol 27, pp. 608-624,Mar. 2007.

[2] X.Sheng and C.J.C Jones. A, Theoretical model for ground vibration from trains generated by vertical track Irregularities, *J Sound Vib*, Vol. 272, pp. 937-965,Feb. 2004.

[3] X.Sheng, and C.J.C Jones Ground, Vibration generated by a load moving along a railway track", *J Sound Vib*, Vol. 288, pp. 129-156, April. 1999.

[4] Xueping. Duan, and Hongping. Zhu, Application of wavelets to structural dynamic analysis under seismic excitations", *J.Huazhong Univ. of Sci.& Tech*, Vol. 28, No. 11, pp. 75-78, June. 2000.

[5] Forrest .JA and Hunt. HEM, A three-dimensional tunnel model for calculation of train-induced ground vibration, *J Sound Vib*, Vol. 294. No. 4-5, pp. 678-705, Nov. 2006.

[6] Hussein in MFM Vibration from underground railways, *Ph.D. thesis, Department of Engineering, University of Cambridge*, 2004

[7] Hussein in MFM, Hunt HEM. An insertion loss model for evaluating the performance of floating-slab track for underground railway tunnels",*10th international congress on sound and vibration, Stockholm, Sweden*, pp. 25-34

[8] Zhang Pu, "Dynamic response of two shield tunnels driven up and down in close proximity duo to subway train's vibrating loads", *Ph. D. thesis. Tongji University*, 2001.