Dynamic analysis of bridges due to earthquakes, winds and moving vehicles using pseudo-excitation method

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ABSTRACT: An innovative and highly efficient random vibration series of algorithms — the pseudo-excitation method (PEM) — and its effective applications in bridge dynamics are presented. PEM transforms stationary random vibration equations into simple harmonic vibration equations; and transforms non-stationary random vibration equations into ordinary equations of motion of structures subjected to deterministic time-history loading. Therefore not only are the solution processes considerably simplified, but also the computational effort is greatly reduced while the numerical results remain highly accurate. This method has now been widely used in the Chinese engineering community, and has been adopted and recommended by the Chinese official Guidelines for Seismic Design of Highway Bridges (2008). It has also been described in detail in the Vibration and Shock Handbook (2005, CRC Press) and the Bridge Engineering Handbook (2013, CRC Press). By means of PEM, 3D flutter-buffet CQC-based analysis has been successfully performed for the 1650m main-span Xihoumen bridge, the second longest suspension bridge in the world, located in the well-known typhoon region Zhou-Shan Islands, in the East China Sea. In addition, PEM has also become a widely-used research and design tool for vehicle engineering in China, including vehicle-bridge dynamic interaction problems. A finite element model for power spectral analysis of a high-speed train coach with 720924 degrees of freedom is presented. Along with a brief introduction to PEM, this presentation will also show a number of practical engineering examples which have successfully used PEM in the related research and design.

KEY WORDS: Pseudo-excitation method; Random vibration; Long span bridge; Earthquake; Wind; Vehicle.

1 INTRODUCTION

In the design of long-span bridges, the spatial effects of earthquakes, including the wave passage effect, the incoherence effect, and the local site effect, must be taken into account [1-2]. The random vibration method can fully account for the statistical nature as well as the spatial effects of earthquakes, and so has been widely regarded as a very promising method. Unfortunately the very low computational efficiency has become a bottle-neck for its practical use.

In the past 20 years, a very efficient method, known as the pseudo-excitation method (PEM), has been developed by the authors and their colleagues to cope with the above computational difficulty [3-9]. This method can easily compute the 3D random seismic responses of long-span bridges using finite element models with many thousands of degrees of freedom (DOF) on a small personal computer, in which the seismic spatial effect is accounted for accurately. This method has been applied to the design of some important long-span bridges in China, e.g. to the No 2 Nanjing Yangtze River Bridge [10] and Qiongzhou Strait Bridge [11]. Based on extensive research by many scholars and engineers, the Chinese official document “Guidelines for Seismic Design of Highway Bridges” JTG/T B01-01-2008 [12] has formally recommended the pseudo-excitation method as a basic tool for seismic analysis of long-span bridges, which will further push forward the progress of design and construction for long-span bridges. PEM has also been introduced by whole chapters respectively in the “Vibration and Shock Handbook 2005” [7] and “Bridge Engineering Handbook 2013” [8].

By means of PEM, the 3D flutter-buffet CQC-based analysis of Hong-Kong Tsing-Ma suspension bridge was performed and extensively studied [13,14]. Although its 3D finite element model involves 2400 mutually coherent wind-gust excitations applied simultaneously on its cables, towers and deck, the 3D fully coupled flutter-buffet CQC analysis was still performed accurately and efficiently only using a personal computer. Recently, PEM has also been successfully used in the wind-resistant design of the 1650m main-span Xihoumen bridge [15], which is the second longest suspension bridge in the world located in Zhou-Shan Islands, a well-known typhoon region in the East China Sea. The dynamic analysis of the buffet-caused internal force distribution over the pylons is of great importance in the design of this bridge. In addition, PEM has also become a widely-used tool in the research and design of various vehicles, including cars [16,17], maglev trains [18,19], high-speed trains [20-23], as well as vehicle-bridge dynamic problems [24,25].
2 PSEUDO EXCITATION METHOD FOR STATIONARY RANDOM VIBRATION ANALYSIS

2.1 A Bridge Subjected to Single Stationary Random Excitations

Consider a linear system subjected to a zero-mean stationary random excitation with a given power spectral density (PSD) \( S_m(\omega) \). Suppose that for two arbitrarily selected responses \( y(t) \) and \( z(t) \), the auto-PSD \( S_y(\omega) \) and cross-PSD \( S_{yz}(\omega) \) are desired. If \( H_y(\omega) \) and \( H_z(\omega) \) are the corresponding frequency response functions, and if \( x(t) \) is replaced by a sinusoidal excitation

\[
\ddot{x} = S_m(\omega) \exp(i\omega t) \tag{1}
\]

the responses of \( y(t) \) and \( z(t) \) would be

\[
y = S_m(\omega)H_y(\omega) \exp(i\omega t) \quad \text{and} \quad \ddot{z} = S_m(\omega)H_z(\omega) \exp(i\omega t). \tag{2}
\]

It can be readily verified that [6-8]

\[
\ddot{y} = S_m(\omega)H_y^*(\omega) \exp(-i\omega t) \cdot S_m(\omega)H_y(\omega) \exp(i\omega t) = |H_y(\omega)|^2 S_m(\omega) = S_y(\omega)
\]

\[
\ddot{z} = S_m(\omega)H_z^*(\omega) \exp(-i\omega t) \cdot S_m(\omega)H_z(\omega) \exp(i\omega t) = |H_z(\omega)|^2 S_m(\omega) = S_z(\omega)
\]

If \( y(t) \) and \( z(t) \) are two arbitrarily selected random response vectors of the structure, and \( \ddot{y} = a_y \exp(i\omega t) \) and \( \ddot{z} = a_z \exp(i\omega t) \) are the corresponding harmonic response vectors due to the pseudo excitation (1), it can also be proved that the PSD matrices of \( y(t) \) and \( z(t) \) are

\[
S_y(\omega) = \ddot{y}^* \ddot{y} = a_y^* a_y \tag{4}
\]

\[
S_z(\omega) = \ddot{z}^* \ddot{z} = a_z^* a_z \tag{5}
\]

This means that the auto- and cross-PSD functions of two arbitrarily selected random responses can be computed using the corresponding pseudo harmonic responses.

Now, consider a structure subjected to a single seismic excitation. Its equations of motion are

\[
M \ddot{y} + C \dot{y} + K y = -ME \ddot{x}_s(t) \tag{6}
\]

in which: \( M, C \) and \( K \) are its mass, damping and stiffness matrices; \( y \) is its displacement vector; the ground acceleration \( \ddot{x}_s(t) \) is a stationary random process with known PSD \( S_{x_s}(\omega) \); and \( E \) is a given constant vector, indicating the distribution of inertia forces. Let the pseudo ground acceleration be

\[
\ddot{x}_s(t) = \sqrt{S_{x_s}(\omega)} \exp(i\omega t) \tag{7}
\]

Substituting Eq. (7) into Eq. (6) gives the pseudo equations of motion

\[
M \ddot{\hat{y}} + C \dot{\hat{y}} + K \hat{y} = -ME \sqrt{S_{x_s}(\omega)} \exp(i\omega t) \tag{8}
\]

Using the first \( q \) normalized modes for mode-superposition leads to [26]}

\[
\ddot{\hat{y}}(t) = a_j(\omega) e^{i\omega t} = \sum_{j=1}^{q} y_j(\omega) H_j(\omega) \sqrt{S_y(\omega)} e^{i\omega t} \tag{9}
\]

in which \( \phi_j, H_j \) and \( y_j \) are the \( j \)th mass normalized mode, frequency response function and mode participation factor, respectively.

According to PEM

\[
S_y(\omega) = \ddot{y}^* \ddot{y} = \ddot{\hat{y}}^* \ddot{\hat{y}} = a^*_j a_j^T \tag{10}
\]

Substituting Eq. (9) into Eq. (10) and expanding it gives the conventional complete quadratic combination (CQC) algorithm

\[
S_y(\omega) = \sum_{j=1}^{q} y_j(\omega) \phi_j^T H_j(\omega) H_j(\omega) \phi_j(\omega) \tag{11}
\]

This means Eqns. (10) and (11) are mathematically identical to each other. However, the computational effort required by Eq. (10) is approximately only \( 1/q^2 \) of that required by Eq. (11). Hence, Eq. (10) is also known as the fast CQC algorithm.

2.2 A Bridge Subjected to Multiple Stationary Random Excitations

Consider a linear structure subjected to a number of stationary random excitations, which are denoted as an \( m \) dimensional stationary random process vector \( x(t) \) with known PSD matrix \( S_m(\omega) \). The equation of motion is

\[
M \ddot{y} + C \dot{y} + K y = x(t) \tag{12}
\]

The PSD matrix is Hermitian and so it can be decomposed, e.g. by using its eigenpairs \( \psi_j \) and \( d_j \) \( (j=1, 2, ..., r) \), into

\[
S_m(\omega) = \sum_{j=1}^{r} d_j \psi_j^* \psi_j \tag{13}
\]

in which \( r \) is the rank of \( S_m(\omega) \). Next, constitute \( r \) pseudo harmonic excitations

\[
\ddot{\hat{x}}_j(t) = \sqrt{d_j} \psi_j \exp(i\omega t) \tag{14}
\]

By applying each of these pseudo harmonic excitations, two arbitrarily selected response vectors \( y_j(t) \) and \( z_j(t) \) of the structure, which can be displacements, internal forces or other linear responses, may be easily obtained and expressed as

\[
\ddot{\hat{y}}_j(t) = a_j(\omega) \exp(i\omega t) \tag{15}
\]

\[
\ddot{\hat{z}}_j(t) = a_j(\omega) \exp(i\omega t) \tag{16}
\]

The corresponding PSD matrices can be computed by means of the following formulas [3]

\[
S_y(\omega) = \sum_{j=1}^{r} \ddot{\hat{y}}_j(\omega) \ddot{\hat{y}}_j^*(\omega) = \sum_{j=1}^{r} a_j^* a_j^T \tag{17}
\]

\[
S_z(\omega) = \sum_{j=1}^{r} \ddot{\hat{z}}_j(\omega) \ddot{\hat{z}}_j^*(\omega) = \sum_{j=1}^{r} a_j^* a_j^T \tag{18}
\]

The way used to decompose \( S_m(\omega) \) into the form of Eq. (13) is not unique. In fact, if there are too many random excitations, the complex form Cholesky scheme may be a more efficient and convenient way to do it, i.e. \( S_m(\omega) \) is decomposed into
\[ S_m(\omega) = L^T D L = \sum_{j=1}^{m} d_j \Gamma_j^T \quad (r \leq m) \]  

(19)  

in which \( L \) is a lower triangular matrix with all its diagonal elements equal to unity and \( D \) is a real diagonal matrix with \( r \) non-zero diagonal elements \( d_j \).

Clearly, when the bridge under consideration is subjected to the action of multiple seismic or wind-gust excitations, the PSD matrix of the excitations \( S_m(\omega) \) can be used to yield a finite number of harmonic excitations. The resulting \( r \) groups of harmonic responses will lead to the PSD functions for such responses, which are exact numerical solutions.

3 PSEUDO EXCITATION METHOD FOR NON-STATIONARY RANDOM VIBRATION ANALYSIS

3.1 Problems with a single evolutionary random excitation

Consider a linear system subjected to an evolutionary random excitation

\[ M \ddot{y} + C \dot{y} + Ky = p(t) \dot{x}(t) \]

(20)  

in which \( g(t) \) is a slowly varying modulation function, while \( x(t) \) is a zero-mean stationary random process with auto-PSD. \( p \) is a constant vector describing the distribution and intensity of the excitations. \( S_m(\omega) \). The deterministic functions \( g(t) \) and \( S_m(\omega) \) are both assumed to be given.

In order to compute the PSD functions of various linear responses due to the action of \( f(t) \), the pseudo excitation has the form

\[ \tilde{f}(\omega,t) = g(t) \sqrt{S_m(\omega)} \exp(\text{i}\omega t) \]

(21)  

while the pseudo excitation equation is

\[ M \ddot{\tilde{y}} + C \dot{\tilde{y}} + K \tilde{y} = p(t) \dot{\tilde{x}}(t) \]  

(22)  

Suppose that \( y(t) \) and \( z(t) \) are two arbitrary selected response vectors, and \( \tilde{y}(\omega,t) \) and \( \tilde{z}(\omega,t) \) are the corresponding transient responses due to the pseudo excitation \( \tilde{f}(\omega,t) \) with the structure initially at rest. It has been proved that [4]

\[ S_{yn}(\omega,t) = \tilde{y}^T(\omega,t) \tilde{y}(\omega,t) \]  

(23)  

For cases with fully coherent excitations, partially coherent excitations, and non-uniformly modulated evolutionary random excitations, the corresponding pseudo-excitation algorithms are very similar to those for the stationary random excitation cases [4,7].

3.2 Problems with a single non-uniformly modulated evolutionary random excitation

If the structure is subjected to a non-uniformly modulated evolutionary random excitation \( f(t) \), which is usually expressed in terms of a Riemann-Stieltjes (RS) integration

\[ f(t) = \int \alpha A(\omega,t) e^{\text{i}\omega t} d\alpha(\omega) \]  

(25)  

in which \( A(\omega,t) \) is a given non-uniform modulation function, while \( \alpha \) meets the following equation

\[ E[da^2(\omega)\alpha(\omega)] = S_m(\omega)\delta(\omega_\alpha - \alpha) d\alpha \]  

(26)  

where \( S_m(\omega) \) is the auto-PSD of the stationary random process \( x(t) \). Although the random excitation \( f(t) \) contains a random integration, the pseudo excitation

\[ \tilde{f}(t) = A(\omega,t) \sqrt{S_m(\omega)} e^{\text{i}\omega t} \]

(27)  

does not contain such an integration. Thus Eq. (22) becomes

\[ M \ddot{\tilde{y}} + C \dot{\tilde{y}} + K \tilde{y} = pA(\omega,t) \sqrt{S_m(\omega)} e^{\text{i}\omega t} \]

(28)  

Clearly, the solution of this equation is exactly the same as for Eq. (22) except for the modulation functions, i.e. using \( g(t) \) or \( A(\omega,t) \). The formulae for PSD computations, i.e. Eqs. (23) and (24), are still valid.

3.3 A bridge subjected to multiple non-stationary random excitations

For problems with uniformly modulated evolutionary random excitations, Eq. (20) should be revised as [7,8]

\[ M \ddot{y} + C \dot{y} + Ky = p(\omega,t) \dot{y}(t) \]

(29)  

in which \( [R] \) is a given constant matrix representing the positions of applied forces, and \( f(t) \) is a vector consisting of \( m \) elements, each representing an evolutionary random process. It has the form

\[ f(t) = \begin{bmatrix} g_1(t) \dot{x}_1(t) \\ g_2(t) \dot{x}_2(t) \\ \vdots \\ g_m(t) \dot{x}_m(t) \end{bmatrix} = Gx(t) \]

(30)  

in which \( g_i(t) \) is the modulation function of the \( i \)th excitation, i.e. the \( i \)th diagonal element of the \( m \times m \) diagonal matrix \( G \); the \( m \times m \) matrix \( S_m(\omega) \) is the known PSD matrix of a zero-mean stationary random vector process, which can be decomposed in the manner of Eqs. (12) or (13), to constitute the following pseudo excitation

\[ \tilde{f}_j(t) = [D_j, \tilde{g}_j(t)] p e^{\text{i}\omega t} \quad (j = 1,2,...,r) \]

(31)  

By substituting Eq. (22) into the right-hand side of Eq. (20), the pseudo responses \( \tilde{y}_j(\omega,t) \) and \( \tilde{z}_j(\omega,t) \) can be obtained by means of the precise integration method (PIM) [27], and the corresponding time dependent PSD matrices would then be

\[ S_{yn}(\omega,t) = \sum_{j=1}^{r} \tilde{y}_j(\omega,t)^T \tilde{y}_j(\omega,t) \]  

(32)  

\[ S_{zn}(\omega,t) = \sum_{j=1}^{r} \tilde{z}_j(\omega,t)^T \tilde{z}_j(\omega,t) \]  

(33)
For problems with non-uniformly modulated excitations, the algorithm is exactly the same provided the modulation function $g(t)$ in Eq. (30) is replaced by $A_i(\omega, t)$ from the following expression:

$$f(t) = \begin{cases} A_1(\omega, t)x_1(t) \\ A_2(\omega, t)x_2(t) \\ \vdots \\ A_n(\omega, t)x_n(t) \end{cases}$$

and

$$\begin{bmatrix} A_1(\omega, t) \\
A_2(\omega, t) \\
\vdots \\
A_n(\omega, t) \end{bmatrix} \begin{bmatrix} x_1(t) \\
x_2(t) \\
\vdots \\
x_n(t) \end{bmatrix} = Gx(t) \quad (34)$$

4 RANDOM VIBRATION ANALYSIS OF VEHICLE-BRIDGE SYSTEMS USING PEM

For vehicle-bridge systems, the random loading vector has the following form

$$F(t) = \Gamma(t)r(t) \quad (35)$$

in which $\Gamma(t)$ is a transform matrix, which describes the positions of all wheels; $r(t)$ describes the surface unevenness at all contacting points between the wheels and the bridge deck, which is usually assumed to be zero-mean valued. Such positions $x_i$ vary with time $t$. If the vehicle has $n$ points in contact with the deck, $r(t)$ has the form

$$r(t) = [r(x_1), r(x_2), \ldots, r(x_n)] \quad (36)$$

Provided that the vehicle runs over the bridge at a uniform speed $V$, then

$$x_i = vt + \Delta x_i \quad (37)$$

in which $\Delta x_i$ represents the distance of the $i$-th wheel between its position at $t = 0$ and the coordinate origin (e.g. one end of the bridge). According to the time-space coordinate transformation $x = vt$, if the PSD of $r(x)$ is $S_r(\Omega)$, then the PSD of $r(t)$ would be

$$S_r(\omega) = S_r(\Omega)/V; \quad \omega = \Omega V = 2\pi V/\lambda \quad (38)$$

in which $\omega$ (rad/s) is the angular frequency in the time domain, and $\Omega$ (rad/m) is the angular frequency in the space domain. $\lambda$ (m) is the wavelength associated with the surface unevenness. The PSD matrix of $F(t)$ can be expressed as

$$S_{FF}(\omega) = \Gamma(t) \begin{bmatrix} 1 & e^{i\omega t_1} & \ldots & e^{i\omega t_n} \\
1 & e^{i\omega t_1} & \ldots & e^{i\omega t_n} \\
\vdots & \vdots & \ddots & \vdots \\
1 & e^{i\omega t_1} & \ldots & e^{i\omega t_n} \end{bmatrix} \Gamma^T(t)S_r(\omega)$$

It is pseudo-excitation has the following form

$$\tilde{F}_e(t) = \Gamma(t)[e^{-i\omega t_1}, e^{-i\omega t_1}, \ldots, e^{-i\omega t_n}]^T \sqrt{S_r(\omega)}e^{i\omega t} \quad (40)$$

Arbitrary pseudo response can be calculated by

$$\tilde{u}(\omega, t) = \int_0^t H(t, \tau) \tilde{F}_e(\tau) d\tau \quad (41)$$

According to Eq. (23), one obtains

$$S_y(\omega, t) = \tilde{u}(\omega, t)\tilde{u}^T(\omega, t) \quad (42)$$

This is the pseudo-excitation method of the non-stationary random vibration in the space domain. When a vehicle is running on a bridge, using this method combined with the scheme proposed by Yang [24] will conveniently carry out the strict non-stationary random vibration analysis of the coupled vehicle-bridge system, in which the interaction between two independent systems is performed [25]. Note that this PEM-based method does not need any unevenness sample of the bridge surface in order to perform the step-by-step numerical integration. Instead it computes the power spectral density functions of various required responses directly by means of the PSD functions of the surface unevenness of the bridge deck. Therefore it is a strict random vibration approach, and is highly efficient. As its further development, Zhang [28] took the vehicle and bridge as an independent time-variant system, and also obtained strict non-stationary random vibration solutions by combining the PIM [27] with PEM.

5 APPLICATIONS OF PEM TO BRIDGE AND VEHICLE DYNAMICS

5.1 No 2 Nanjing Yangtze River Bridge Subjected to Multiple Seismic Random Excitations

In the past thirty years, many very long bridges have been built in China. Most of them are located in earthquake active regions. The problem of how to evaluate their ability to withstand strong earthquakes has received much attention. Many scholars and engineers have made great efforts to tackle this difficult problem. They not only investigated international well-known achievements, e.g. [1,2], but also developed their own methods in combination with their projects. In this process, PEM has become a widely used and very useful tool. Fan and his colleagues at Shanghai Tong-Ji University [10] used PEM to investigate the seismic behavior of No 2 Nanjing Yangtze River Bridge, as shown in Figure 1. It is a five-span dual-tower cable stayed bridge with total length 1238m and tower height 195.4m. Three hundred modes were used for mode-superposition when using PEM.
Both wave passage effects and incoherence effects were taken into account. For directions along the bridge and across the bridge, the horizontal shear wave velocity takes values between 500 m/s and 1000 m/s. Using 3D beam elements and based on a whole 3D FEM analysis, it was concluded that the wave passage effect is a significant factor for the computation of various dynamic responses. Up to 40% differences may be caused in comparison with those due to uniform seismic ground excitations.

5.2 Seismic Analysis for Shamen-Zhangzhou Cable-Stayed Bridge

Shamen-Zhangzhou Bridge (i.e. Zhangzhou Bay Bridge) as shown in Figure 2 is a cable-stayed highway bridge between two important Chinese cities Shamen and Zhangzhou, which are both very close to Taiwan Island. This bridge opened in May 2013. Its main span is 780 m, the total width of the deck is 37 m and the total length of the bridge is 11.7 km. It has four pylons and 296 cables which used 687,000 cubic meters of concrete and 115,000 tons of steel cables.

The PEM, the response spectrum method and the time-history approach were used by a research group in Dalian University of Technology in the seismic analysis of this long-span bridge [11]. The results were compared to one another in detail. It was shown that if the ground motion is assumed to be uniform, various dynamic results from the three methods are very close to one another. However, if the ground motion is assumed to be inhomogeneous, i.e. with the wave passage effects and incoherence effects considered, such dynamic results would be quite different. The probabilistic results by using PEM may produce significant and more reasonable changes with very economical computation cost. The results due to the time history method are not only very time consuming, but are also quite divergent depending on the ground acceleration samples adopted.

5.3 Wind-Induced Flutter-Buffet Analysis for Tsing-Ma Suspension Bridge

Hong Kong’s Tsing-Ma long suspension bridge has a main span of 1377 m between the Tsing-Yi tower in the east and the Ma-Wan tower in the west carrying a dual three-lane highway on the upper level of the bridge deck and two railway tracks and two carriageways on the lower level within the deck. The height of the towers is 206 m, the north and south main cables are 36 m apart and are accommodated by the four saddles located at the top of the tower legs in the main span. The bridge deck is a hybrid steel structure continuing between the two main anchorages. It is suspended by suspenders in the main span and the Ma-Wan side span. On the Tsing-Yi side the deck is supported by three piers rather than suspenders. A three-dimensional dynamic finite element model was established for the Tsing-Ma bridge after the completion of deck welding connections. Three dimensional Timoshenko beam elements with rigid arms were used to model the two bridge towers. The cables and suspenders were modelled by cable elements accounting for geometric nonlinearity due to cable tension. The FE model has 1010 elements, 769 nodes and 2254 DOF. The fully coupled buffeting analysis was carried out by using the PEM in the frequency domain. This method can readily handle a bridge deck with significantly varying structural properties and mean wind speed along the deck, to make full use of the finite element bridge models already developed for the static and eigenvalue analyses.

The buffeting response of the bridge deck obtained from PEM is in good agreement with that computed using Scanlan’s method [29]. The aeroelastic damping was found to reduce the vertical response of the bridge deck, and the aeroelastic effects on the torsional vibration of the Tsing-Ma bridge are significant. The multimode effects are considerable on the vertical motion and torsional motion but not on the lateral motion of the bridge deck. Intermode effects can be neglected for the two modes in either lateral motion or vertical motion or torsional motion, but intermode effects should be considered for the aeroelastically coupled vertical and torsional modes of similar shape. The results
from the present approach reveal that the buffeting of the bridge deck considerably impacts the buffeting of towers and main cables, whereas the buffeting of towers and main cables moderately affects the lateral vibration of bridge deck.

5.4 Wind-Induced Flutter-Buffet Internal Force Analysis for Xihoumen Sea-Crossing Suspension Bridge

![Xihoumen Suspension Bridge](image)

This bridge links Zhou-shan islands and Ningbo City of Zhejiang Province, located in the world-known super-strong typhoon region in the East China Sea. The fourth bridge of an island–linking project, it is a north-south bridge transversally crossing over Xihoumen water of 7.7km in length and 2.5km in width. It is a double span continuous suspension bridge. It ranks first among the steel box-girder suspension bridges in China and the second in the world. Its main span is 1650 m long, and the length of each main cable is 2882m. In fact, as the second longest suspension bridge in the world, it is only shorter than the Akashi Strait Bridge in Japan (with main span 1991m).

How to evaluate the wind-induced flutter-buffet internal force distribution as well as the safety is one of the key challenges in its design. In order to investigate the safety of the north tower in its longest cantilever status in the construction stage, in normal service status and in the emergency status when the strongest gale within a century takes place, a 3D finite element model for the north pylon was meticulously established. The flutter-buffet analysis was performed under 0° and 90° wind yaw angles. The wind-induced structural internal force responses and the gust response factors of the pylon were studied by Dr. G. Liu and his colleagues in China Communications Construction Company (CCCC) Limited Highway Consultants Co. using PEM [15]. The numerical results show that the wind-induced bending moment responses have a gradually increasing trend, whereas the gust factors have a gradually decreasing trend with the decrease of the pylon elevation for all the above three statuses. Since this bridge opened in 2009, it has encountered the attacks of a few very strong typhoons, and the safety of the bridge has been fully confirmed.

5.5 Pseudo-excitation Analysis for the riding quality of Maglev Trains

![Shanghai Pudong Airport Maglev Train](image)

The Shanghai Maglev Train is a magnetic levitation train line from Shanghai Pudong International Airport to the outskirts of central Shanghai near Shanghai, China. It is the first and only commercial high-speed maglev line in the world with a normal speed of 430 km/h. Construction of the line began in March 2001 and public service commenced in January 2004. The train set and tracks were manufactured using the German-originated Transrapid technology. Two commercial maglev systems had predated the Shanghai system—the Birmingham Maglev in the United Kingdom and the Berlin M-Bahn. Both were low-speed operations and had closed before the opening of the Shanghai Maglev Train due to reliability and other problems. In fact, so far there are still quite a lot of remaining problems with the system. The opening of this maglev line has therefore attracted many Chinese scholars to research them in order to further improve the performance of such trains so that they can be further developed in China.

Clearly, the reliability and comfortability of the maglev train are of great concern. Dr. Zhou and his colleagues at the Institute of Railway and Urban Mass Transit of Tongji University have published several research papers covering these aspects [18,19], in which PEM was used as a basic tool. For track-vehicle systems, the unevenness of the track surface is the main reason that causes vehicle random vibration. In addition, the time lags between the forces acting on the front and rear wheels will result in the “wave-passage effect”. Previously, such analyses were considered rather difficult, and the inefficient time domain integration scheme was used to calculate such random vibration approximately. Zhou et al. [18] found that PEM can deal with such problems very conveniently and efficiently. Based on the TR08 maglev train model, they obtained the required PSD functions of some responses, and so easily obtained the accurate Sperling stability index at the body center, which is the key parameter necessary for the design of maglev trains.
5.6 Probabilistic Reliability Analysis of Vehicle-Bridge Systems by means of PEM

Presently, PEM is playing an important role in the development of automobiles [16,17], maglev trains [18,19] as well as high-speed trains[20-23] in China. Train-bridge coupled random vibration caused by the track surface roughness has also received much attention in the research and development of high-speed trains[20,25,28].

The unevenness of the road/track surface is the most important cause of vehicle vibration. Because of the complexity and low efficiency of the traditional random vibration approach, previously, when calculating such random vibration, the vehicles were modeled as multi-mass systems with ten or at most 20 degrees of freedom. Such approximate models cannot reflect the high frequency components in real random signals, and cannot evaluate the random fatigue life due to the dynamic stress concentration. In addition, the power spectral density functions of the random surface unevenness are generally represented by one or a small number of time history samples for approximate random vibration calculation. Clearly, this is not a strict random vibration approach.

The PEM provides a strict and highly efficient random vibration approach to such vehicle-bridge problems. Even for 3D finite element vehicle-bridge models with tens of thousands of DOF, accurate random vibration analysis has now become very simple. Therefore PEM has not only been widely used in the automobile industry to improve the dynamic performance, but also in the high-speed train industry. In terms of PEM and much relevant research success, Dalian University of Technology has cooperated with a high-speed train manufacturer to develop the special techniques and corresponding software in order to improve the comfort and reliability of the high-speed trains. They have completed such a module HiPEM [21] integrated into the SiPESC (Software Integration Platform for Engineering and Scientific Computation) [23]. As the track can be regarded as an infinitely long and periodical substructural chain, therefore the symplectic mathematical method [27] has been well applied in order to further accelerate the computing speed [28,30].

Figure 6 shows a finite element model of a coach of the CRH2 High-Speed Train widely used in China. This model consists of 3D beam, plate and block elements, and has 720924 DOF in all. When it runs on the track, the “wave passage effect” was taken into account in the random vibration analysis by means of PEM. Figure 7 gives the distribution (cloud graph) of the vertical acceleration standard differences of a high-speed train coach body and the international standard ISO-2631 is used to evaluate the riding comfort. All computations were performed on an ordinary PC.

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