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Fundamental model of structure-borne vibration transmission in buildings using the portal frame approach

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ABSTRACT – Vibration coming from mechanical services are often the source structure-borne noise sources in buildings. The transmitted vibration waves from these machines can activate the building structures to vibrate and radiate audible low frequency noise inside the building. This paper proposes the development of a generic analytical model of a 2D portal frame structure consisting of column and beam elements. The proposed model is use to predict the structural response of a multi-story portal frame building in order to understand the behavior of the structure with propagating vibration waves. The result is validated using the FE model which gives good agreement.

1. INTRODUCTION

As a number of building service equipment, such as ventilators and air conditioners, cooling tower and mechanical parking tower are installed in buildings, inevitably, the machine's operation induced structure-borne vibration can be a common 'noise and vibration problem' in the building.

Existing studies of the structure-borne transmission in buildings are those due to ground-borne vibration from railway trains [1-2] which proposed finite element (FE) and boundary element (BE) scheme analysis of vibration from railway tunnels. The study concentrates on the structure and acoustic response of a multi-story portal frame office building up to a frequency of 150 Hz to the passage of a Thalys high-speed train at constant velocity. The study presented the modes of the structure and the structure response shown in Figure 1. According to this study, a full three-dimensional FE/BE model takes approximately 1000-2000 times longer than the two-dimensional analysis.

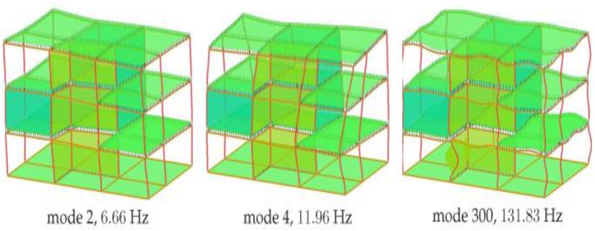

Figure 1 Examples of modes in a multi-storey building model.

Li and Wu [3] presented an analytical model to determine dominant vibration frequencies of a rail bridge. The work was based on the force method to obtain the power flows within a coupled vehicle-track-bridge system, the point mobility of the system and the dynamic interaction forces connecting the various subsystems. A similar analytical method will be used to investigate the structure response in this project, but due to the input from the mechanical service equipment.

2. METHODOLOGY

2.1 Theoretical element

One of the two most important elements in a framework is a column of a building. This type of element has the property of load bearing capability in the axial direction and longitudinal wave travels along the column. According to Thompson (1993) [4], the dynamic stiffness matrix of column is defined as,

$$K = EA\begin{bmatrix} jk_c & -jk_c \\ -jk_c e^{-jk_c L_y} & jk_c e^{jk_c L_y} \end{bmatrix}\begin{bmatrix} 1 & 1 \\ e^{-jk_c L_y} & e^{jk_c L_y} \end{bmatrix}^{-1} \quad (1)$$

where E is the Young's modulus, A is the cross sectional area, L_y is the length of the column in the direction of y, and the wave-number is $k_c = \omega\sqrt{\rho / E}$.

A beam can be assumed as a horizontal structure connecting to the columns and the foundation elements of a floor. For bending in a beam, bending waves are assumed to propagate through the beam. Euler-Bernoulli beam theory is applied [5], the dynamic stiffness matrix is equal to:

$$K = EI\begin{bmatrix} jk^3 & -jk^3 & -k^3 & k^3 \\ k^2 & k^2 & -k^2 & -k^2 \\ -jk^3 e^{-jkLy} & jk^3 e^{-jkLy} & k^3 e^{-kLy} & -k^3 e^{kLy} \\ -k^2 e^{-jkLy} & -k^2 e^{-jkLy} & k^2 e^{kLy} & k^2 e^{kLy} \end{bmatrix} \times \begin{bmatrix} 1 & 1 & 1 & 1 \\ -jk & jk & -k & k \\ e^{-jkLy} & e^{jkLy} & e^{-kLy} & e^{kLy} \\ -jke^{-jkLy} & jke^{jkLy} & -ke^{-kLy} & ke^{kLy} \end{bmatrix}^{-1} \quad (2)$$

where I is the second moment of cross sectional area and the wave-number is $k = \sqrt{\omega}\left(\rho A / EI\right)^{1/4}$.

2.2 One Floor Portal Frame Model

Figure 2 shows an example of a simple portal frame model representing a building with one floor. This frame is developed in order to explain how the stiffness matrix of each element is assembled into one matrix. The roof top is a combination of two beam elements where the force is applied between element *b* and *c*. The size of the general dynamic stiffness matrix of the connections between elements is 8×8.

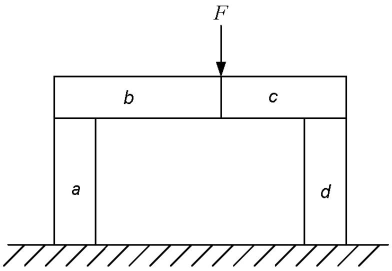

Figure 2 Injection force at the mid-bay of the floor.

The general dynamic stiffness matrix of the element is as follows,

$$\begin{bmatrix} a_{11} & a_{12} & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{21} & a_{22}+b_{11} & b_{12} & b_{13} & b_{14} & 0 & 0 & 0 \\ 0 & b_{21} & b_{22} & b_{23} & b_{24} & 0 & 0 & 0 \\ 0 & b_{31} & b_{32} & b_{33}+c_{11} & b_{34}+c_{12} & c_{13} & c_{14} & 0 \\ 0 & b_{41} & b_{42} & b_{43}+c_{21} & b_{44}+c_{22} & c_{23} & c_{24} & 0 \\ 0 & 0 & 0 & c_{31} & c_{32} & c_{33}+d_{11} & c_{34} & d_{12} \\ 0 & 0 & 0 & c_{41} & c_{42} & c_{43} & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{21} & 0 & d_{22} \end{bmatrix} \quad (3)$$

where the matrix $[a_{11} \;\; a_{12}; \;\; a_{21} \;\; a_{22}]$ is the matrix referring to the component *a* and *a*, *b*, *c* and *d* in Eq. (3) refers to the wave amplitude propagating in the column and the beam.

3. RESULTS AND DISCUSSION

The displacement at any point can be estimated by first finding the wave amplitudes using Eq. (1). The vibration amplitude is described here in terms of velocity and vibration velocity level in decibels is used in this study is $L_v = 20 \times \log_{10}\left(v / v_{ref}\right)$, where L_v is the velocity level in decibels, v is the rms velocity amplitude, and $v_{ref} = 1 \times 10^{-9}\, \mathrm{ms}^{-1}$ is the reference velocity amplitude.

As shown in Figure 3, the result from analytical model is validated using FE model which gives good agreement. In this analytical model, two types of materials are selected to model the beam and column of a building. The properties of the building material used in the model are shown in Table 1.

The analytical is then used to predict the motion of the structure due to the influence of the external force. As show in Figure 4, the operating deflection shapes (ODS) is estimated using the ratio between displacements at all points of the beam with displacement at the mid-bay point where the force is injected, U_{midbay}. The ratio is defined as $\mathrm{X} = \mathrm{real}\left(U(x) \times e^{\,j\varphi} / U_{\mathrm{midbay}}\right)$.

Table 1 Material Properties

	Beam	Column
Density, ρ (kg/m^3)	2000	2800
Young's Modulus, *E* (GPa)	2.6×10^{10}	3×10^{10}
Damping loss factor, η	0.012	0.006

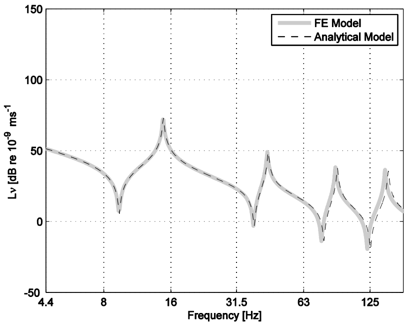

Figure 3 Vibration velocity level at the mid-bay point of the floor.

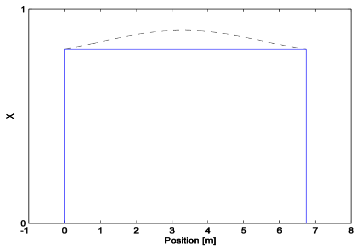

Figure 4 ODS of the structure at 14.8 Hz

4. CONCLUSIONS

A single portal frame model has been proposed to simulate vibration of a one-storey building. The model will be extended to a complex portal frame consisting five floors to achieve a model closest to the real aplication.

5. REFERENCES

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