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Numerical and experimental investigation on structure-borne sound transmission in multilayered concrete structures

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ABSTRACT

Environmental vibrations in cities are transmitted to buildings and propagate through the buildings via complex paths composed of the structural elements in the building, such as concrete slabs, beams, and columns. In this study, the transmission characteristics of such structure-borne sound in building structures composed of concrete were experimentally and numerically investigated. The vibration and radiated sound characteristics of a five-storey concrete structure obtained experimentally through an excitation test using the hammering method and numerically through wave-based numerical calculations are presented and compared. In this study, the finite-difference time-domain (FDTD) method, which treats the target structure as a composition of two-dimensional plate and one-dimensional beam elements to enable a low-cost calculation, is applied as a wave-based scheme. The propagation characteristics of the vibration and sound within the same floor and across different floors were investigated by considering various combinations of receiver and source points, and the structure-borne sound transmission characteristics of a concrete structure with frame elements are discussed.

1. Introduction

Various types of environmental vibration sources originating from facility buildings, road and railway traffic, and building construction produce vibrations around buildings in cities, and these vibrations contribute to structure-borne sound transmission via building structures. The environmental vibrations excite the buildings and are transmitted through the bodies of the structures. Because reducing the transmission of vibrations through a structural body is difficult after construction has been completed, having an accurate grasp of structure-borne sound characteristics during the preconstruction phase is important.

Various articles have reported experimental investigations on the source characterization of structure-borne sound sources [1,2], whereas fewer papers have reported case studies on measurements targeting the structure-borne sound transmission of large structures. In such large structures, it is difficult to obtain the transmission characteristics of vibrations with a high signal-to-noise (S/N) ratio, especially when the source and receiver points are spatially distant from each other. A powerful excitation force with a magnitude similar to that generated by railway traffic can be applied in a controlled test as a

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practical example of an excitation source for a structure-borne sound measurement [3]. However, in building structures, the application of such a powerful excitation force under controlled settings is difficult. To vibrate a heavy structure using conventional sources, such as shakers, a large, massive facility that can input a sufficient amount of energy into the structure is necessary. Bovey has investigated a method of measuring the vibration propagation on a railway structure through impact excitation by a large hammer [4], and the transfer functions of structures can be directly obtained using this method. Obtaining structure-borne sound transmission characteristics with a sufficiently high S/N ratio at receivers distributed over a wide range in a large building structure would significantly contribute to improving the prediction accuracy of the vibroacoustic characteristics of the building.

As a prediction method for vibration propagation, the statistical energy analysis (SEA) method is broadly applicable and has been used in aerospace engineering [5], investigations of structure-borne sound on ships [6], and architecture [7]. For example, Craik et al. applied the SEA method to a practical case study on the prediction of structure-borne sound in a building [8], and Hynná et al. calculated the structure-borne sound transmission of a large structure of a ship by reducing the amount of work required to model the ship for SEA calculations [9]. SEA enables the prediction of a large-scale structure model; however, it is difficult to obtain sufficient accuracy at relatively low frequencies, at which the wave motion of the vibration has a greater influence on the propagation mechanism. In contrast, numerical techniques, such as the finite element method (FEM), boundary element method (BEM), and finite difference method (FDM), are powerful measures for predicting the wave motion of the structure and have the advantage of high accuracy when modeling the physical phenomena of the vibration. Among these methods, the FEM is frequently applied to vibration analysis in the engineering field. Mace and Manconi investigated the wave propagation of two-dimensional homogeneous structures by wave finite element analysis [10]. Renno and Mace developed a hybrid method combining finite element and wave finite element models and obtained numerical results on the reflection and transmission properties of the joints connecting waveguides [11]. Wang and Unal simulated the free vibration of rectangular plates of stepped thicknesses using the spectral FEM [12]. Yang et al. applied the wavelet FEM to the wave motion analysis of an arch structure, presenting the influence of cracks on wave propagation [13]. Burlayenko et al. presented a comparative study on the free vibration of various composite plates using different plate finite element models [14]. Furthermore, the numerical parameters of the coupling loss factor concerning SEA have been estimated using the FEM [15].

In more practical cases, the FEM has been applied to the damage identification of materials [16,17]. In such studies, the vibration of various types of complex structures have been investigated in detail, whereas case studies on the vibration propagation of large-scale structures, such as multilayered buildings, using numerical techniques including the FEM have not been reported. The biggest bottlenecks when applying such a numerical method to large-scale structures are the computational costs of the required calculation time and the load on the memory, which essentially increase in proportion to the degree of freedom of the model. In contrast to the FEM, the finite-difference time-domain (FDTD) method has been broadly utilized in electromagnetics, elastodynamics, acoustics, and other fields since its introduction by Yee [18]. However, its application to the problem of vibrations that propagate mainly in the mode of bending waves is still in development; however, similarly described phenomena are found in the field of acoustics and elastodynamics.

The physical phenomenon of elastic wave propagation has been investigated by using the FDTD scheme as follows. Chew and Liu proposed a new absorbing boundary condition utilized to implement the perfect matched layer for elastic waves [19]. Schroder and Scott applied a finite difference model to the detection of buried land mines [20]. Sato proposed an FDTD scheme with a diagonally staggered grid system to model wave propagation in anisotropic solids [21,22]. Toyoda et al. have been investigating the application of the FDTD calculation to the prediction of the vibroacoustic stimulation of a concrete structure [23,24]. Although the precision of the three-dimensional models described above contributes to the accuracy of the results, the computational load of the discretization of the target fields using the three-dimensional mesh required for this type of model may be higher. From the viewpoint of the structure-borne sound characteristics in the buildings, the bending wave propagation on plate-like and beam-like structures can be the dominant factor enabling the vibration transmission. To effectively calculate bending wave propagation on such a frame structure consisting of slabs, beams, and columns, the discrete spatial modeling of the target structure as a system of one-dimensional beam and two-dimensional plate elements is more effective from the viewpoint of reducing the total number of degrees of freedom.

To realize the effective calculation of structure-borne sound, the authors previously investigated a low-cost prediction method [25–28] applying the FDTD method, which can effectively model a structure with low-dimension elements. This method has the decisive advantages of rendering the time variation of the wave propagation as an animation and enabling the quantitative evaluation of the simulation results. In the proposed method, to prevent an increase in the computational cost, the simulated structure consists of dimension-reduced elements: one-dimensional beam and/or two-dimensional plate elements. The radiated sound characteristics are simulated by a method of coupled acoustic and dimension-reduced vibration FDTD methods. In our previous paper [28], the vibroacoustic propagation characteristics of a simple medium-sized two-layer wall-type concrete structure without beam or column elements were simulated using a dimension-reduced model. However, a building with a more complex frame-type structure consisting of beams and columns, as well as wall-type elements of floors and walls, should be investigated as a more practical case.

In this paper, the structure-borne sound transmission characteristics of a building structure consisting of concrete slabs, walls, beams, and columns were measured through impulsive excitation using a large hammer and compared with the FDTD simulation results obtained using the dimension-reduced model. This paper is organized as follows. Section 2 describes the details of the numerical theory, the modeling scheme of the damping effect of the concrete structure, and the dispersion