The Simulation of Footstep-Induced Floor Vibration Signal

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Many indoor human sensing applications had been proposed based on the structural vibration sensing system, including identification, tracking, localization [1, 2, 4]. However, the system performance varies under different deployment environment conditions, since the acquired data waveform and spectrum distribution impacted by the deployment environment. To improve the scalability and robustness of the vibration sensing system, we explore to quantify the impact from the deployment environment on the system performance, and use the quantified environmental information to optimize the system deployment. For example, the structure elements (i.e., pillar, bearing wall, beam) can impact the propagation distance of the vibration signal. We can select the best deployment location (i.e., highest sensing range) if the impact of the structure elements on the vibration signal propagation is quantified.

Controlled experiments are usually used to analyze the relationship between two factors (i.e., deployment environment and system performance). For the structural vibration sensing system, there are multiple environmental factors are coupled to impact the vibration signal, which make it's difficult to conduct a control experiment in real world. We plan to develop a simulation platform to simulate the vibration signals in different deployment environments, and use the simulated data to explore the metric which measure the impact from the deployment environment.

We establish a simulator to simulate the acquired signal in different environments. The simulation contains three steps: 1) vibration generation, 2) wave propagation, and 3) signal acquisition.

1 VIBRATION GENERATION

We use a single degree of freedom model [5] to simply the structure and consider the footstep-induced vibration belongs to a natural oscillation.

1.1 Single Degree of Freedom System

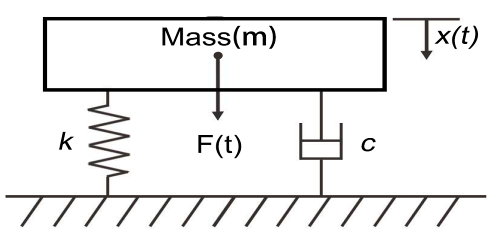

Figure 1: The prototypical single degree of freedom oscillator [5]. The structure be simplified as a signal degree of freedom oscillator, contains three components: mass, spring, and damper.

Figure 1 shows a prototype of single degree of freedom system (SDOF). The are three components: mass, spring, and damper. In this prototpye, the mass has no stiffness or damping, the spring had no mass or damping, the damper had no stiffness or mass.

Based on Newton's second law of motion, the external force $F(t)$ can be represent as:

$$F(t) = ma(t) + cv(t) + kx(t) \quad (1)$$

$$= m\ddot{x}(t) + c\dot{x}(t) + kx(t) \quad (2)$$

Where m, k, and c is the mass, spring constant, and damping coefficient of the structure. a, x, and v is the acceleration, displacement, and velocity of the structure. Based on the definition of acceleration, velocity, and displacement, we have: $a = \dot{v} = \ddot{x}$, and $v = \dot{x}$.

1.2 Natural oscillation

We separate one footstep fall event into two stages: 1) knock the floor, 2) entirely attach on the floor. We assume that the force between the foot and the structure is zero in the second stage (ignore the gravity of the leg). Whit this assumption, the floor in the second stage belongs to a natural oscillation system. The first stage of footfall event only impact the initial conditions of the second stage.

Based on Eq. 2, for a natural oscillator, we have:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = 0 \quad (3)$$

We define $w_n = \sqrt{k/m}$ and the damping ratio as $\zeta = \frac{c}{2w_n m}$. When $\zeta < 1$,

$$x(t) = Ae^{-\zeta w_n t}\cos(w_d t + \theta).$$

By solve the above equation with the initial conditions (initial displacement x_0 and initial velocity $v0$), we have

$$x(t) = [\frac{x_0}{\sqrt{1-\zeta^2}}\cos(w_d t - \theta) + \frac{\sqrt{v_0}}{w_d}\sin(w_d t)]e^{-\zeta w_n t}.$$

Where $\theta = \arctan\frac{\zeta}{\sqrt{1-\zeta^2}}$

1.3 Signal Generation Simulation and Analysis

In the simulation, we assume the area of the floor is 2 m x 5 m, and the height is 0.3 m. We assume the density of the concrete floor is around 2400 Kg/m^3. The density of the wooden floor is in the range of 260 Kg/m^3 to 1200 Kg/m^3. We set the mass of the concrete floor as 7200 Kg, and the mass of the wooden floor as 1000 Kg.

The reference stiffness of different floors is in the range of 10^7 N/m to 80^7 N/m [3]. In this simulation, we set the stiffness (k) of the concrete floor as $5 * 10^7$ N/m, and set the stiffness of the wooden floor as $6 * 10^7$ N/m. We set the damping coefficient of the concrete floor as 10^5 Kg/s, and the damping coefficient of the wooden floor as $4 * 10^4$ Kg/s. The initial displacement is 2 mm, and the initial velocity is 0.2 m/s.

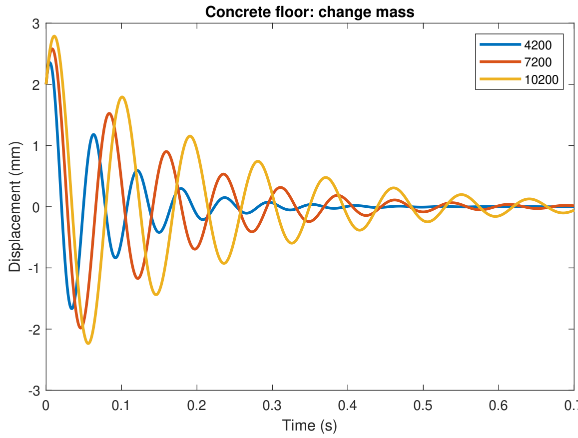

Figure 2: Changing the density (mass) of the concrete floor. The legend is the mass (kg) of each floor.

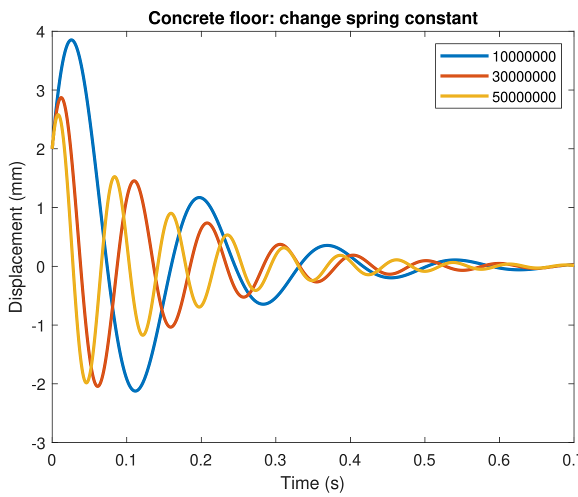

Figure 3: Changing the spring constant of the concrete floor. The legend is the spring constant.

Density analysis. Figure 2 shows the induced vibration signal in different concrete floor which have different density. First, we set the initial condition for different as the same. The heavier floor has more energy at the beginning. This is why the amplitude of the vibration signal on the heavier floor is higher than the amplitude on the lighter floor. Second, the damping frequency on the lighter floor is larger than on the heavier floor.

Stiffness analysis. Figure 3 shows the impact of stiffness on the induced vibration signal. In this simulation, we change the spring constant of the concrete floor, and control the other parameters.

Elasticity analysis. Figure 4 shows the impact of the damping coefficient on the induced vibration signal. We can observe that the damping coefficient only impacts the attenuation rate. A higher damping coefficient floor has less amplitude attenuation rate.

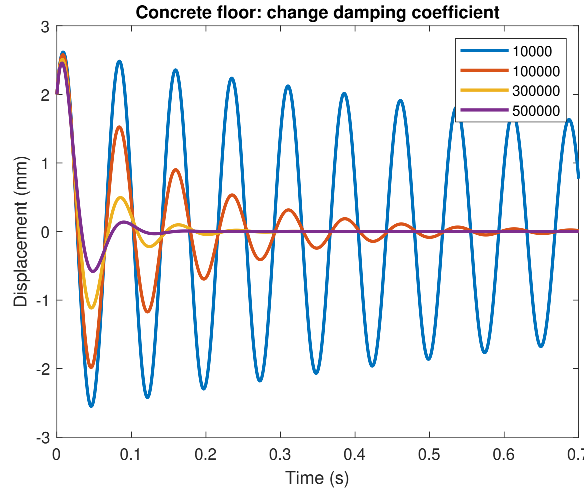

Figure 4: Changing the damping coefficient of the concrete floor.

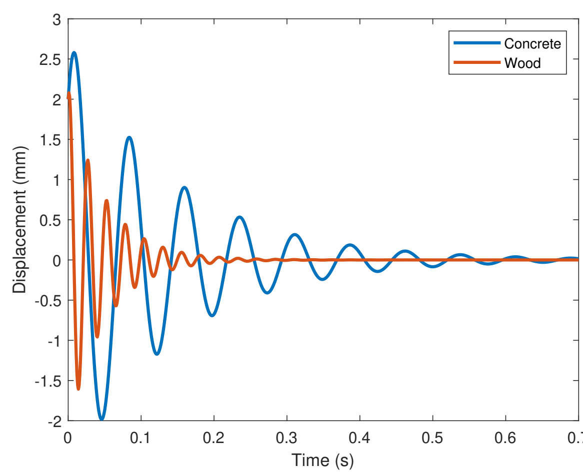

Figure 5: Comparing the concrete floor and wooden floor.

Material analysis. Figure 5 shows the induced vibration signal on two floors. In the simulation, $m_w = 0.13 * m_c$, $k_w = 1.2 * k_c$, $c_w = 0.5 * c_c$. m_w, k_w, and c_w is the mass, spring constant, and damping coefficient of the wooden floor, respectively. The mass of the wooden floor is obviously less than the concrete floor, so the amplitude of the vibration signal on the wooden floor is less than the amplitude of the vibration signal on the concrete floor. The damping coefficient of the wooden floor is less than the concrete floor, but the signal duration on the wooden floor is less than the signal duration on the concrete floor. This is because the natural frequency on the wooden floor is more than three times higher than the natural frequency on the concrete floor. The attenuation rate of two nearby peaks on the wooden floor is less than on the concrete floor, which indicates that the damping coefficient on the wooden floor is less than on the concrete floor.

2 VIBRATION SIGNAL PROPAGATION

The induced signal propagates from the impact location to the sensor location. In our previous experiment, we find that the structure characteristics also can impact the waveform and spectrum distribution of the signal. We plan to use finite element analysis to simulate the signal propagation. We will post it once we finish it.

3 SENSOR ACQUISITION

Different sensors measure the different characteristics of the vibration wave. For example, the geophone sensor measures the velocity of the vibration wave (i.e., $\dot{x}(t)$). But the accelerometer sensor measures the acceleration of the vibration wave (i.e., $\ddot{x}(t)$). On the other hand, the circuit design and implementation also can impact the acquired signal/data. We will post our simulation solution once we finish it.

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