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Characterizing human activity induced impulse and slip-pulse excitations through structural vibration

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ABSTRACT

Many human activities induce excitations on ambient structures with various objects, causing the structures to vibrate. Accurate vibration excitation source detection and characterization enable human activity information inference, hence allowing human activity monitoring for various smart building applications. By utilizing structural vibrations, we can achieve sparse and non-intrusive sensing, unlike pressure- and vision-based methods. Many approaches have been presented on vibration-based source characterization, and they often either focus on one excitation type or have limited performance due to the dispersion and attenuation effects of the structures. In this paper, we present our method to characterize two main types of excitations induced by human activities (impulse and slip-pulse) on multiple structures. By understanding the physical properties of waves and their propagation, the system can achieve accurate excitation tracking on different structures without large-scale labeled training data. Specifically, our algorithm takes properties of surface waves generated by impulse and of body waves generated by slip-pulse into account to handle the dispersion and attenuation effects when different types of excitations happen on various structures. We then evaluate the algorithm through multiple scenarios. Our method achieves up to a six times improvement in impulse localization accuracy and a three times improvement in slip-pulse trajectory length estimation compared to existing methods that do not take wave properties into account.

1. Introduction

Human activities induce excitations on the ambient structure (e.g., floors, walls, tables) when performing activities. Characterizing them, especially tracking the source location of the excitation, enables further inference of the human activity information. This activity information can be used in many smart building applications, such as child/patient monitoring, customer behavior analysis, and ubiquitous user input. This structural vibration-based sensing, compared to other methods including vision-, RF-, mobile-, acoustic-, and load-based sensing, enables sparse and non-intrusive sensing on people [1–6]. More detailed comparison between our structural vibration based methods and other sensing approaches can be found in

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Section 8.1. These excitations mainly fall into two categories: impact induced impulse excitations (such as footstep, object dropping, door closing, tapping) and friction induced slip-pulse excitations (such as drag a chair, swipe on a surface) [7]. The challenges for vibration based excitation sources tracking include 1) the variance of excitation types and 2) the dispersive nature of the structure materials [8].

Many methods have been presented to track human activity induced excitation through structural vibrations. In particular, works focus on the trajectory estimation of the human induced excitation on the wall by recognizing the specific vibration signal pattern that linked to the trajectory of the excitation [9,10]. These approaches are based on the repetition of the trajectory caused signal pattern, therefore requiring large-scale training data to establish such a relationship. Pham et al. track the human induced excitation sources directly, which is sensitive to medium variation [11–13]. Works have also been done on localizing the human induced excitation such as footsteps and heartbeats [14–16] by taking wave properties into account to handle the dispersive structures. However, these works focus on particular applications.

In this paper, we present our robust structural vibration sensing system that enables various types of human induced excitations (impulse and slip-pulse) tracking under multiple structural conditions. To address the challenges for vibration based excitation sources tracking and achieve high tracking accuracy, we first study the wave properties of different types of excitations to understand the dispersion, propagation and attenuation of impulse and slip-pulse signals. Then we utilize our understanding on wave dispersion, propagation and attenuation for impact-induced impulse and friction-induced slip-pulse to design the algorithm that can obtain accurate Time Difference of Arrival (TDoA) estimations despite these effects. Finally, we use multilateration to calculate locations of the excitation sources and hence achieve tracking. To validate our method, we performed a series of experiments that evaluate the system by computing the accuracy of locating various types of excitation sources with different structural characteristics. The main contributions of this paper are:

- We study the wave properties of human-induced impulse and slip-pulse excitation in structures to enable vibration-based non-intrusive human activity characterization.
- We present our characterization algorithm that reacts to each excitation based on the analytic models of different waves to resolve dispersion and reflection effects and achieve accurate tracking on various structures.
- We characterize and evaluate our method through structures of various materials and sizes with different impulse and slip-pulse excitations for multiple applications.

The rest of the paper is structured as follows: First of all, we provide the background knowledge that supports our work in Section 2. Next, we present the sensing system and explain the characterization of different excitations in Section 3 followed by the example applications in Section 4. Furthermore, we describe our experiment setup in Section 5, and discuss the experiment results in Section 6. In addition, we discuss the possible extensions of this work in Section 7 and the prior work that is related to our system in Section 8. Finally, we conclude our work in Section 9.

2. Background

Different human-induced excitations induce different types of vibration signals. These signals mainly fall into two categories: the impulse and the slip-pulse signals [7,12]. In this section, we introduce the physics behind them, including 1) properties of waves induced by different types of excitations and 2) wave propagation in solids. Our signal characterization algorithm is designed based on the wave properties introduced here.

2.1. Impulse v.s. slip-pulse waves

The impulse and slip-pulse excitation on structures produce different mechanical waves. The former induces surface waves due to point impact force while the latter produces body waves due to friction.

Impact-induced vibrations are produced by a single point of contact on structures [7], such as a foot striking on a floor or a pen tapping on a table. The force applied to a structure causes it to deform. As the contact point is relieved of the force, the structure retracts due to its elasticity. This elasticity generates surface waves propagating outward from the point of contact, similar to ripples generated by dropping a stone into water [7].

Friction-induced vibrations are observed when two objects slide against each other. Stick-slip is a general form of friction that induces vibrations [17,18], such as a chair dragging on a floor or a pen swiping on a table. When an object slides on a structure, it will ‘stick’ because of static friction and the unevenness of the structural material, then the force applied to it causes it to overcome the static friction and slide or ‘slip’ [17,19]. When these two states are alternating, the friction between the object and the structure changes between static friction and kinetic friction [19]. Since typically static friction is larger than kinetic friction, such alternating friction causes a sudden jump in the velocity of the movement, resulting in slip pulse [17,19] along the swipe. These slip pulses induce a wave that travels at an angle in the material as a combination of different types of waves dominated by body wave [19]. In this work, we leverage this body wave to locate the slip pulses and estimate the trajectory of the consecutive slip pulses.