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# Impact localization in dispersive waveguides based on energy-attenuation of waves with the traveled distance

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ABSTRACT

An algorithm is introduced to solve the general multilateration (source localization) problem in a dispersive waveguide. The algorithm is designed with the intention of localizing impact forces in a dispersive floor, and can potentially be used to localize and track occupants in a building using vibration sensors connected to the lower surface of the walking floor. The lower the wave frequencies generated by the impact force, the more accurate the localization is expected to be. An impact force acting on a floor, generates a seismic wave that gets distorted as it travels away from the source. This distortion is noticeable even over relatively short traveled distances, and is mainly caused by the dispersion phenomenon among other reasons, therefore using conventional localization/multilateration methods will produce localization error values that are highly variable and occasionally large. The proposed localization approach is based on the fact that the wave's energy, calculated over some time window, decays exponentially as the wave travels away from the source. Although localization methods that assume exponential decay exist in the literature (in the field of wireless communications), these methods have only been considered for wave propagation in non-dispersive media, in addition to the limiting assumption required by these methods that the source must not coincide with a sensor location. As a result, these methods cannot be applied to the indoor localization problem in their current form. We show how our proposed method is different from the other methods, and that it overcomes the source-sensor location coincidence limitation. Theoretical analysis and experimental data will be used to motivate and justify the pursuit of the proposed approach for localization in a dispersive medium. Additionally, hammer impacts on an instrumented floor section inside an operational building, as well as finite element model simulations, are used to evaluate the performance of the algorithm. It is shown that the algorithm produces promising results providing a foundation for further future development and optimization.

## 1. Introduction

Estimating the location of an energy source given a set of measured variables is an interesting research problem that has been investigated from different application points of view. An energy source could be an earthquake, an explosion, an antenna transmitting electromagnetic waves, vocal cords of a person talking, etc. Each source generates a wave that

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propagates away from the source in a specific medium (waveguide). Depending on the characteristics of the generated wave and the waveguide, the wave might travel different distances and have different speeds. If several sensors are deployed at different locations in the waveguide, such that they measure a certain feature of the traveling wave, then those sensor measurements in addition to prior knowledge of the characteristics of the traveling wave can be utilized to estimate the source location. For example, an earthquake generates a seismic wave having two components; longitudinal P and flexural S waves. Seismic stations estimate the earthquake's origin by utilizing sensor measurements in addition to knowledge of the facts that P and S waves have different propagation speeds, and the fact that seismic waves have circular wavefronts propagating radially away from the source.

In a similar fashion, the location of an impact force acting on a plate or a floor can be estimated using sensors that measure the generated vibration in the waveguide. In this study, a new technique for impact localization in a dispersive floor is proposed. *In particular, out-of-plane acceleration measurements from accelerometers installed underneath the floor will be used, in conjunction with novel algorithms, to localize hammer impacts. This study involves an initial algorithm evaluation phase using finite element (FE) model simulations of a thin plate, followed by a real-life experiment on an instrumented floor inside a fully operational building. The proposed new localization approach is computationally efficient and is based on utilizing the fact that traveling waves lose energy as they travel away from the source.*

Utilizing an accelerometer sensor network for impact localization can be helpful in structural health monitoring and has security applications such as locating an intruder, or an active shooter [1]. Furthermore, accelerometers can be placed in hidden and hard to reach locations—e.g., underneath floors—which potentially provides a tamper-proof and non-intrusive system of event localization.

The main challenge in localizing impact forces in a dispersive waveguide is *dispersion*. Dispersion in solids means that higher frequency components of the resulting traveling wave will travel at a non-linearly increasing speeds. Therefore, for an impact source, having a wide-band of frequency components, dispersion will distort the wave-packet shape as it travels away from the source. As will be explained later in Section 2, dispersion is more noticeable in the lower frequency components of the traveling wave, which contains most of the energy generated by an impact force such as a hammer or a footstep [2,3]. Another problem that adds to the distortion of the traveling wave, and further complicates the localization problem, is *frequency-dependent damping*, in which higher frequency components of the traveling wave are subjected to higher attenuation with the traveled distance. In Section 2, we explain that larger variations in the attenuation rate take place in the higher frequency components of the traveling wave, and we hypothesize that, for an impact force, the shape of the resultant wave-packet will be less distorted by frequency-dependent damping compared to the wave-packet distortion due to dispersion.

Other sources of error and challenges exist in the practical floor localization problem including inhomogeneity in the floor material, cracks, sensor noise, errors in the coordinates of the sensor locations (for methods that depend on knowledge of sensor coordinates), wave reflections at boundaries, and interference between waves generated by more than one impact source acting on the waveguide simultaneously.

Dispersion, in addition to the other previously mentioned challenges, complicate the localization problem and provide a fundamental challenge worthy of attention. Therefore, this paper attempts to tackle the localization problem addressing some of these challenges.

Several localization methods can be found in the literature. These methods can be broadly categorized into time difference of arrival (TDOA) methods [4–12], direction of arrival (DOA) [13–17], pattern-matching [18–21], and wave's energy loss with traveled distance [22–25].

Conventional TDOA localization works by generating N-1 equations each describing a hyperbola, where N is the number of sensors. Considering, without loss of generality, the $N^{th}$ sensor as a reference sensor, then each equation takes the form $d_i - d_N = v \times (d_i - d_N/v) = v \times (TDOA)$, where $d_i$ is the source-sensor distance, $i = 1, 2, \ldots, N-1, d_N$ is the distance from the source to the reference sensor, and $v$ is the assumed propagation speed. Therefore, it can be seen that conventional TDOA methods assume a single wave propagation speed $v$, thus they are well-suited for localization in non-dispersive waveguides. However, direct application of conventional TDOA techniques in dispersive waveguides will yield unreliable location estimates with an accuracy that is sensor-location dependent and source dependent [8–10]. Nevertheless, it is worth mentioning, that TDOA was applied unconventionally in [5] to locate footsteps in an instrumented floor to localize occupant footsteps. By choosing a possibly different propagation speed for each location estimation and selecting a subset of sensors, sub-meter location accuracy was achieved.

As for DOA techniques, they are based on estimating the bearing of the source from the source's generated wave. DOA is usually represented by an angle measured with respect to a reference line. This angle is referred to as the angle of arrival (AOA) which is determined at a point in the waveguide away from the source, and is defined in a 2-dimensional reference plane (usually the horizontal or vertical plane) as the angle between the projection of the wave's true DOA line and the reference line. If two DOA lines are estimated at two different points, with known locations, in the waveguide, then the intersection point of the two DOA lines will give an estimate of the source's location. DOA localization methods either assume the wavefront is linear when it arrives at the sensors (far-field localization), which cannot be guaranteed in a restricted environment, or assume the availability of sensors measuring the in-plane extensional waves, which are hard to measure in a building floor since they produce measurement levels that are within the sensors' noise floors.