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Investigating the use of multi-point coupling for single-sensor bearing estimation in one direction

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ABSTRACT

Bearing estimation of radially propagating symmetric waves in solid structures typically requires a minimum of two sensors. As a test specimen, this research investigates the use of multi-point coupling to provide directional inference using a single-sensor. By this provision, the number of sensors required for localization can be reduced. A finite-element model of a beam is constructed with a symmetrically placed bipod that has asymmetric joint-stiffness properties. Impulse loading is applied at different points along the beam, and measurements are taken from the apex of the bipod. A technique is developed to determine the direction-of-arrival of the propagating wave. The accuracy when using the bipod with the developed technique is compared against results gathered without the bipod and measuring from an asymmetric location along the beam. The results show 92% accuracy when the bipod is used, compared to 75% when measuring without the bipod from an asymmetric location. A geometry investigation finds the best accuracy results when one leg of the bipod has a low stiffness and a large diameter relative to the other leg.

1. Introduction and motivation

Bearing estimation is a commonly implemented component of emission-source localization, often used in fields such as acoustics [1,2], wireless technology [2], and seismology [3,4]. Bearing estimation relies on extracting directionally dependent properties of a waveform and using this information to estimate the angle-of-arrival (AOA) [5]. Assuming a radially symmetric signal, measurements from a single location do not provide sufficient information for directional inference. The most straightforward approach to overcome this problem is to take measurements from multiple locations. This is often seen in the acoustics and wireless fields where bearing estimation problem is commonly solved using a sensor array [2,5–9]. With this method, the signal is measured at multiple nearby locations, and the phase-shift between the measured signals is used to find a bearing estimate. Alternatively, a rotating sensor design can be implemented [10]. Provided the transmission lasts long enough for a full rotation of the sensor, the orientation of the sensor when the relative amplitude is at a maximum can be taken as the bearing estimate. When considering structural or seismic waves, particle motion can be exploited to perform bearing estimation using a single three-axis sensor [11–14]. This method, however, can have limitations in environments where excitations work predominantly in the out of plane motion [15,16].

This research investigates an alternative bearing estimation method using multi-point coupling that can be applied to structural waves. The proposed method is investigated using a simplified version of the bearing estimation problem, and

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serves as a first look at using sensor-structure coupling to resolve directional ambiguity. While this research implements the concept on a solid structure, the applications extends to both the acoustic and seismic fields if the proper coupling “joint” mechanism can be realized. The primary benefit of this work is in creating a single sensor capable of providing additional information about the location of an excitation source. Short of using multiple sensors in an array, there has been nothing similar to this approach that has been implemented in the literature. Providing directional inference from a single sensor has the potential to reduce the number of sensors required to accurately locate an emission source, or to allow for more efficient redundancy in localization problems where over-determined systems can be better optimized [17]. The work herein investigates the feasibility of using a single sensor to determine the direction of arrival (DOA) of a propagating wave in a solid beam. While the one-dimensional problem is not of particular interest to localization, it provides the initial framework for bearing estimation using a single sensor by considering the effects of an asymmetrically coupled sensor-structure interface.

In dispersive media, the wave train is more complicated than in non-dispersive media due to the nonlinear relationship between frequency and wavenumber [18]. This has the potential to make DOA more difficult to implement in dispersive systems [19], particularly when heavy reflections are present, or the properties of the media are unknown. With the approach investigated herein, there are many approaches to estimate the DOA and their resulting performance would depend on the specific characteristics of the coupled joint. This research does not investigate the optimal method to determine the DOA, but applies a simple method based on matched filtering, using a set of training points and correlation coefficients. This method serves as an investigative tool into the feasibility of the design.

The developed method is applied to a beam model to find the DOA for impacts located at random positions along the beam. The accuracy is used to assess the initial concept, as well as a variety of geometry configurations, which are created by augmenting several parameters from the original design. The effects of uncorrelated white noise are also considered. The results are discussed within the context of localization and future applications are considered. The following section will discuss the model used, and is followed by a series of investigative simulations. After the initial investigations, a correlation approach is developed, followed by a feasibility study. Lastly, various geometric configurations of the bipod are considered.

2. Concept evaluation

A multi-point coupling method is proposed to resolve the bidirectional ambiguity of waves propagating in symmetric, elastic solids by incorporating an asymmetric bipod at the point of instrumentation. The concept design is shown in Fig. 1. Acceleration measurements are taken from the apex of an asymmetric bipod, where an accelerometer would be placed in an experimental setting. By introducing asymmetry, the propagated waveform may be differentiated based on the DOA. For example, a wave traveling along the beam would excite the sensor at both interface locations. Ignoring any coupling between the two interface points, the sensor would first measure the wave as it propagates through the first interface. After a time delay the wave would pass through the second interface and excite the sensor a second time. This would result in measuring the same signal twice, with some amplitude and phase shift. If it is assumed that there is minimal dispersion effects over the short distance between the bipod legs and the soft connection provides only damping, then a wave propagating from the rigid side would first see the signal, followed by the damped version as it passes through the soft connection. If the wave originates from the soft side, a lower energy representation of the signal would arrive first, followed by an amplified version as it passes through the rigid connection. In this example, the DOA would be easily distinguishable using a time domain representation by simply observing which characteristic response is measured first.

With a more realistic representation, inputs from the rigid side of the bipod would couple to the soft side, creating a more complex time-trace. The differences in impacts originating from either side may not be readily distinguishable, but would still be present within the response. It is the purpose of this research to investigate this distinction and compare the results to simply asymmetrically instrumenting the structure (i.e. placing the sensor off-center).

2.1. Model

A model is developed to investigate the performance and accuracy of the proposed asymmetric coupling method. This will be used to determine the DOA of impacts occurring on the left side ($x < 0$) or right side ($x > 0$) of a beam. The model represents

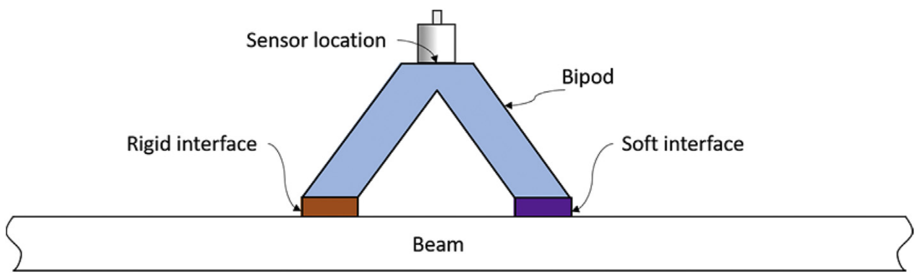

Fig. 1. Concept sketch of the asymmetric bipod design is shown. The DOA affects which interface responds first to the excitation.