Low Power SHM via Frequency-Steerable Acoustic Transducers and Compressive Sensing

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ABSTRACT

The weight penalty and maintenance concerns associated with wiring a large number of transducers have to be addressed for widespread field deployment of Structural Health Monitoring (SHM) systems. Wireless sensors can simplify such deployment. However, a major limitation of wireless ultrasound sensing technology is the incompatibility between the high frequency of the ultrasound signals and the limited data throughput of existing wireless transponders. In this work, a novel transduction concept based on shaped sensors is combined with an innovative acquisition scheme to fulfill two main objectives: 1) to reduce the number of sensing elements; 2) to lower the data throughput with compressive acquisitions.

INTRODUCTION

Ultrasonic Guided Waves (GW) inspection is a popular methodology employed by many Structural Health Monitoring (SHM) systems. GW inspection is typically achieved through phased arrays featuring a large number of piezoelectric sensors [1]. The main drawback of phased arrays is the considerable amount of hardware and data handling required to independently control each element. As an alternative, active and passive structure interrogation through devices with inherent directional capabilities was proposed.

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In [2], directionality is achieved by firing individual wedge sectors of a ring-shaped composite long-range variable-direction emitting radar (CLoVER) transducer. In [3], the directional sensing of incoming waves is achieved by using macro-fiber composite piezoelectric rosettes.

The wavenumber spiral frequency steerable acoustic transducer (WS-FSAT [4]) provides an interesting option for directional structure inspection with further reduction of hardware requirements down to a single, differential channel. The device concept is based on a direction-dependent spatial filtering effect whereby each direction of GW propagation within the [0°; 180°] range is uniquely associated with a dominant frequency component in the spectrum of the actuated/recorded signal. Spatial filtering is provided by the peculiar geometry of this FSAT, which results from inverse Fourier transform of a spiral-shaped distribution in the wavenumber domain.

In this work, such novel device concept is combined with novel data compression procedures. In fact, the transducer output can be efficiently represented in Warped Frequency (WF) bases [5], allowing for a very sparse codification of the informative content associated with the acquired waveform. Such sparsity is the key factor which enables adoption of Compressive Sampling (CS) procedures.

CS is a novel paradigm that has emerged in recent years [6]. CS theory states the possibility of reconstructing a sparse signal by feeding a limited number of measurements into an L1-minimization procedure. In this work, we exploit this framework to obtain a deep sub-Nyquist sampling of FSAT signals, thus dramatically reducing the acquisition bitrate.

WAVENUMBER SPIRAL - FREQUENCY STEERABLE ACOUSTIC TRANSDUCERS

Theory

The concept of frequency-based beam steering stems from a wavenumber analysis of the interaction between guided waves propagating in a thin, plate-like structure and a piezoelectric patch with arbitrary shape. In the wavenumber domain maximum interaction occurs where the dispersion relation of a propagating GW mode intersects the distribution produced by the physical geometry of the piezo-patch.

The orientation θ of the wavevector corresponding to each intersection defines the captured wave propagating direction, while its amplitude k is associated with a specific frequency ω through the dispersion relation $k(\omega)$ of the considered medium. In isotropic media, dispersion characteristics appear as circumferences in the wavenumber domain, with radius $k(\omega)$ dictated by the frequency.

Arranging maxima of the patch wavenumber distribution along a spiral provides intersections in different directions with different iso-frequency dispersion circles, thus providing a one-to-one frequency-direction relation, as schematically illustrated in Figure 1 (a detailed discussion of this transducer design methodology is given in [8]).

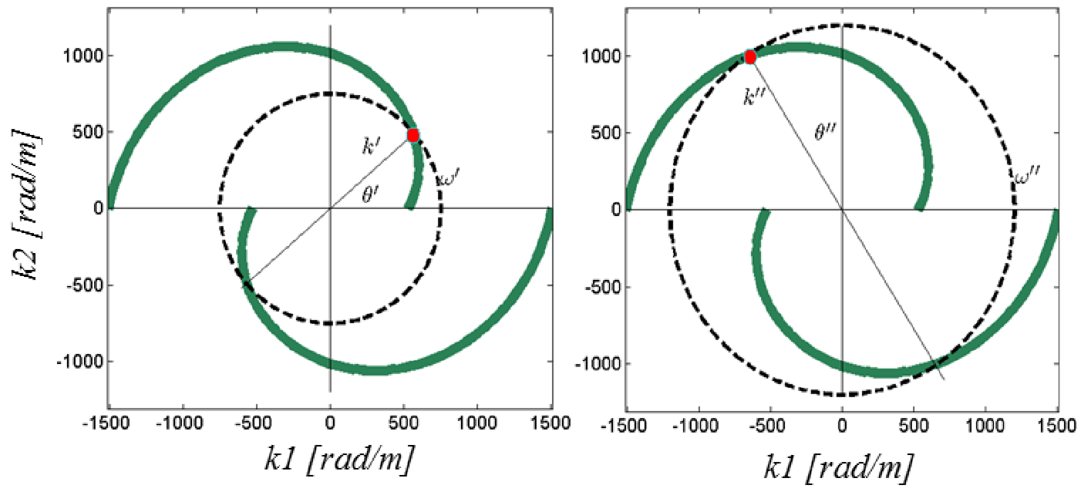

Figure 1. Schematic intersection of a wavenumber spiral distribution (green solid line) with dispersion circumferences at two different frequencies (ω' and ω").

Fabrication

The spatial-domain shape of the transducer is obtained through an inverse 2D Fourier Transform (FT) of the spiral-shaped wavenumber distribution, as shown in Figure 2. Directional properties of the device stem from the resulting non-uniform load modulation, which acts as a spatial filter (Figure (b)). However, the computed spatial distribution is practically unfeasible because it corresponds to continuously varying amplitude modulation over the transducer surface. A simple strategy to achieve a feasible configuration consists of a three-level quantization. This corresponds to a subdivision of the patch into two regions in which harmonic load is applied with opposite polarities, resulting in a two-channel transducer geometry similar to the one reported in Figure 2 (c).

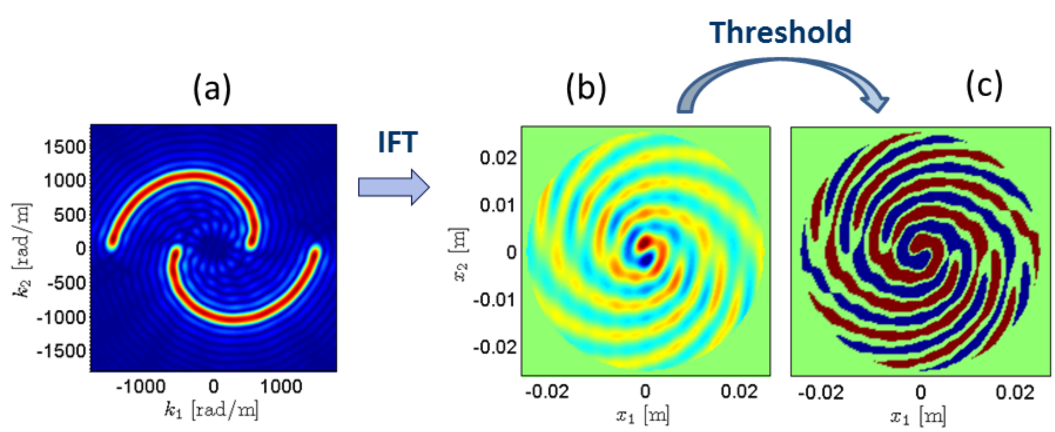

Figure 2. FSAT electrode design procedure: from the load distribution in the wavenumber domain (a) to the one in spatial domain (b) through IFT, then the 3-level quantization produces the electrodes' mask (c).

The discretization procedure enhances the amplitude of secondary lobes, but still this device exhibits the desired spiral shape in the wavenumber domain. Given the electrodes' mask, a rigorous and repeatable fabrication process was developed, based on typical microfabrication techniques, exploiting cleanroom facilities at Georgia Institute of Technology. The process flow patterns the metallization on both sides of a PVDF film according to the desired shape [9].

COMPRESSIVE SENSING

The Random Demodulator Scheme

In order to increase information transmission rates in wireless structural health monitoring applications, it is desirable to construct the most compact possible representations of ultrasonic signals in the digital domain. FSAT signals are sparse if decomposed in warped Gabor dictionaries, in the sense that at each point in time the signals are well-approximated by few element of such dictionary [5].

Recent theoretical advances prove that a signal which is sparse in a given representation can be compressed directly at the sampling stage. The compressed signal can be reconstructed by post-processing a small number of samples. This paradigm has been named analog to information conversion (AIC), and is based on sampling non-adaptively the signal in an incoherent domain and invoking a linear programming procedure after the acquisition step. In our approach, FSAT signals are acquired using the Random Demodulator (RD) scheme [7], sketched in Figure 3.

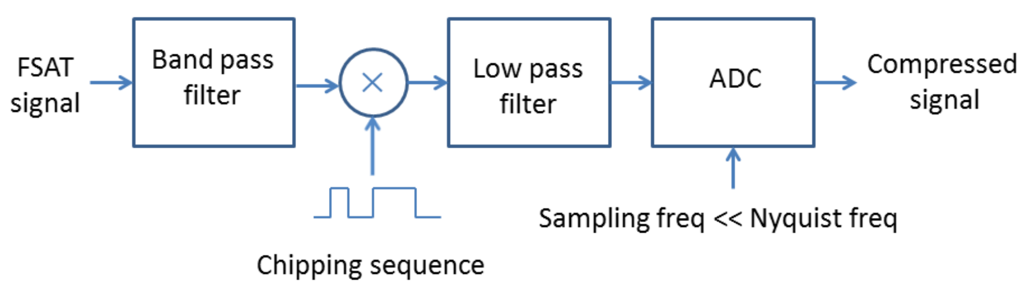

Figure 3. The Random Demodulator Scheme.

The RD signal acquisition system consists in four steps: i) band pass filtering to cancel out contributions of the different modes except the one selected for spiral design; ii) demodulation with a pseudo-random chipping sequence of ±1's.; iii) low pass filtering; and iv) an analog to digital conversion (ADC) performed at a uniform sampling frequency much lower than the one required by Nyquist sampling.

Decompression and Acoustic Imaging

The informative content of the compressed signal can be reconstructed by exploiting convex programming methods, as detailed in [7]. The directional properties of the spiral FSAT enable imaging of 2D areas through the data recorded from a single waveform. The direction-of-arrival is indicated by a peak in the signal spectrum centred around the frequency corresponding to the direction of the incoming wave. The travelled distance is instead evaluated through the estimation of time-of-flight after dispersion compensation, which can be performed by frequency warping (WFT [4]). Thus, a polar image of the monitored area can be obtained by performing a Short-Time Fourier Transform (STFT) of the warped signal. A polar to Cartesian coordinate conversion completes the acoustic imaging computation, which is schematically depicted in Figure 4.

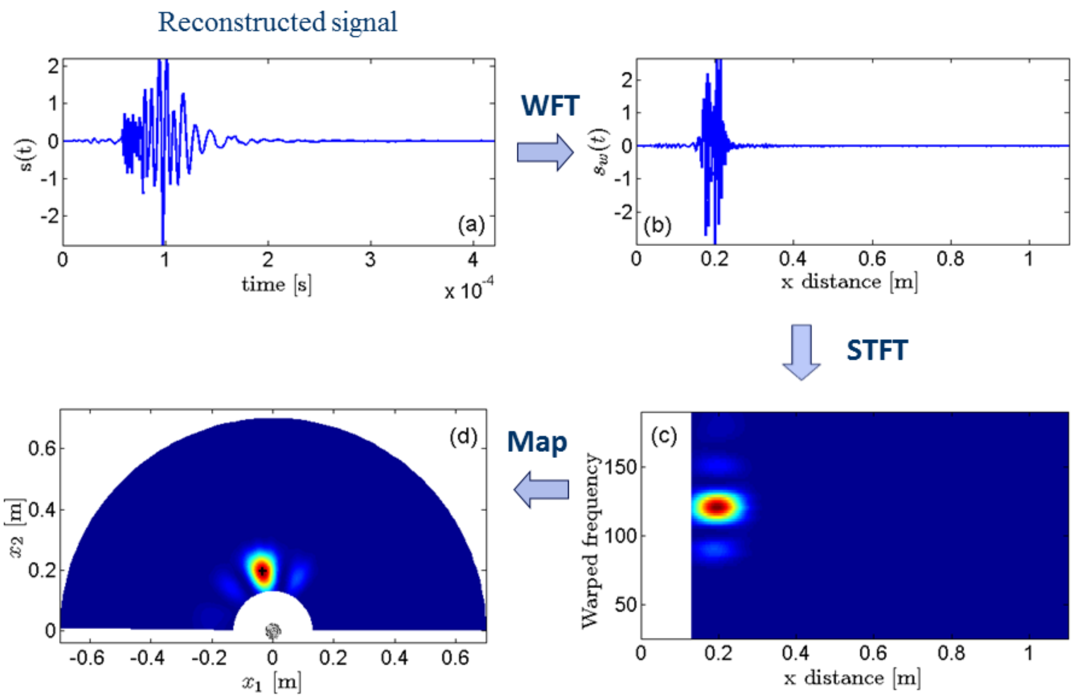

Figure 4. Imaging procedure.

EXPERIMENTAL RESULTS

Localization of broadband acoustic events on aluminium plates is demonstrated by experimental validation. The cleanroom-fabricated FSAT is attached to a 0.75mm-thick Al plate for testing. Plate size is 915 x 915 mm. 5-mm-diameter PZT transducers are used as acoustic sources for testing as they are found to provide relatively uniform excitation within the active bandwidth of the FSATs when driven by a broadband pulser with 900 V output voltage and 10% – 90% rise time of 40 ns. The PZTs are bonded to the plate to provide acoustic sources at different angles. FSAT response is recorded by an oscilloscope.

An AIC procedure based on the RD scheme was implemented. The cut-off frequency of the band pass filter is around 400 kHz therefore the nominal Nyquist frequency should be well above 800kHz. The compressive acquisition was performed by setting the sampling frequency at 290 kHz for the 12 bit ADC. Such selection was shown to be perfectly sufficient to correctly reconstruct both distance and directional information on detected acoustic sources, which are encoded in FSAT output. It is worth noticing that the directional information within the [0°, 180°] angular range is mapped by the transducer into a frequency within the [50, 350] kHz range, which is higher than the compressed sampling frequency.

Figures 5, 6, and 7 compare acoustic imaging results obtained with classical Nyquist sampling and with the proposed compressive sensing strategy. As can be seen, both solutions localize with good accuracy the acoustic sources placed at different angles, despite some spurious artefacts. Compressive sensing allows for over 65% reduction in the sampling rate without significant degradation of imaging results.

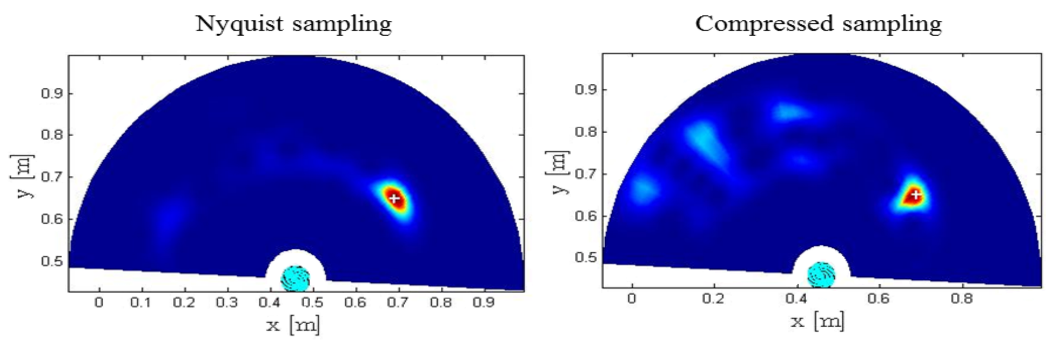

Figure 5. Imaging of 40° acoustic source.

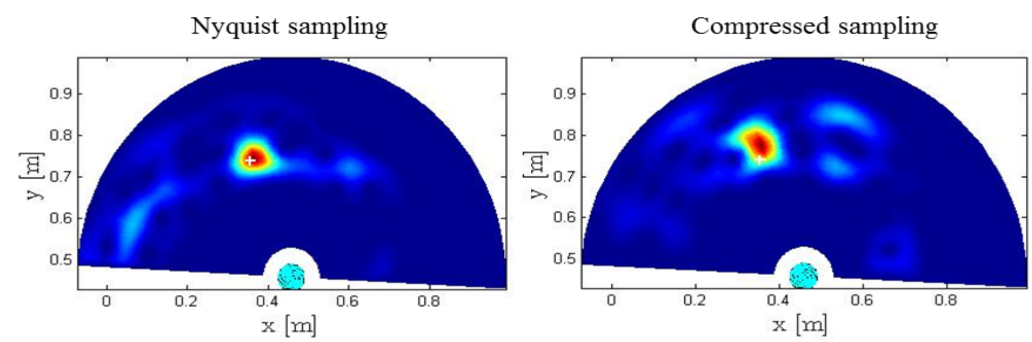

Figure 6. Imaging of 110° acoustic source.

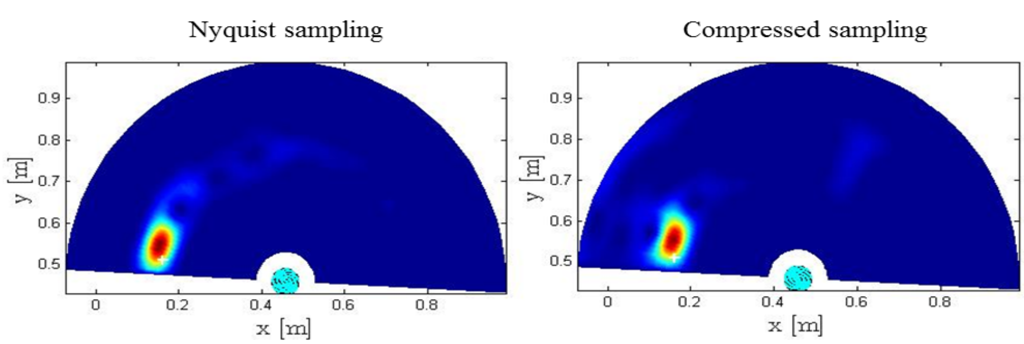

Figure 7. Imaging of 170° acoustic source.

CONCLUSIONS

A CS strategy was applied to signals acquired by Wavenumber Spiral - Frequency-steerable acoustic transducers. WS-FSATs act as spatial filters thanks to their geometry, thus providing a one to one correspondence between the direction of propagation and the spectral content of the actuated/recorded signal. Such novel device concept and associated signal processing tools enable imaging of acoustic events through the differential output signal of a single sensor. The approach based on WF compressive acquisitions greatly boosts hardware and data codification efficiency by enabling SHM of large 2D regions through few sensors and low acquisition bitrates for wireless transmission.

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