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Modeling noisy resonant system response

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ABSTRACT

In this paper, a theory-based model replicating empirical acoustic resonant signals is presented and studied to understand sources of noise present in acoustic signals. Statistical properties of empirical signals are quantified and a noise amplitude parameter, which models frequency and amplitude-based noise, is created, defined, and presented. This theory-driven model isolates each phenomenon and allows for parameters to be independently studied. Using seven independent degrees of freedom, this model will accurately reproduce qualitative and quantitative properties measured from laboratory data. Results are presented and demonstrate success in replicating qualitative and quantitative properties of experimental data.

1. Introduction

All measurement systems and signals contain two types of information: value adding and non-value adding. Measurement systems extract value adding information from a signal while rejecting non-value adding information. Unfortunately, many value-adding signals are difficult to extract in the presence of non-value adding information, such as amplitude or frequency noise.

In experimental measurement systems, the Fast Fourier Transform (FFT) is often used to visually analyze a spectrum and identify key phenomenon, such as resonant peaks. For this reason, Fast Fourier Transforms are widely used in engineering, science, mathematics, and technology, and are employed extensively in both academic and industry circles. While the FFT algorithm is straightforward, extracting patterns and quantifying dynamics and system response from a decomposed signal can often be difficult.

Time domain noise, spectral noise, spectral leakage, and limited resolution all hinder precision spectral measurements. Although advances in high precision, low cost electronics have dramatically reduced electronic signal noise, many mechanical, fluid, and acoustic systems remain limited by physical effects like friction, stiction, and turbulence. Understanding effects created by such non-linearities can help improve measurement system accuracy and assist in separating value-adding information from non-value adding information.

To isolate value-adding from non-value adding information, a model is built to replicate observed experimental data. Experimental data measured in the laboratory shows an overarching resonant structure buried under large amounts of noise. This model decomposes experimental linear acoustic resonant signal data into its constituents to better understand how value adding information can be extracted from mechanical systems in the presence of non-value adding information.

In this research, a signal decomposition that identifies core signal constituents and statistical structure is presented. This

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decomposition provides a foundation upon which a new model for noisy resonant signals and methods is built and used to quantify broad signal noise structure characteristics. This model studies and replicates experimental data using theoretical techniques and methods.

Specifically, this method for exploring and quantifying levels of frequency and amplitude noise relies on both use of Hartigan's dip statistic [1,2], to quantify degrees of bimodality in acoustic signal response, and signal-to-noise ratio. Hartigan's dip statistic is used to measure amplitude noise magnitude while signal-to-noise ratio is used to quantify levels of frequency noise magnitude. With methods for objectively quantifying frequency and amplitude noise magnitudes developed, a seven degree of freedom numerical model (11 controllable parameters) is presented, which simulates acoustic signal response with frequency and amplitude noise, DC offset, windowing, and quantization error.

Linear acoustic resonant data is used for its wide applicability and ease of capture in experimental settings. As the goal of this specific research is to understand acoustic signal statistical structure, non-linear systems are not considered. Additionally, for conditions of information transfer (as is the case in acoustic resonant signals), non-linear systems are not often encountered.

2. Materials and methods

Linear acoustic signals are generated using a fluid-excited, variable-volume Helmholtz resonator; in this research, a 500 mL columnar tube with closed bottom and narrowed neck is used. Such hardware is represented in Fig. 1, although not shown to scale. Air flows over resonator opening, exciting resonator neck columnar air. Steady state excitation causes audible acoustic resonance in proportion to resonator properties, as described by Helmholtz resonator theory [3]. Resonator volume is controlled using variable liquid fill levels.

Acoustic signals are transduced using an Audio-Technica unidirectional, dynamic microphone. Microphone electrical output signal is sampled using an analog-to-digital converter with an upstream analog anti-aliasing filter and blocking capacitor to reject DC and ultra-low frequency noise. A sampling rate of 40 kHz was used with 24-bit resolution and each acoustic signal was sampled for 100 s using National Instruments LabVIEW, yielding 4,000,000 samples.

Resonant frequency is detected by globally maximizing a filtered spectrum. First, experimentally sampled acoustic signals are windowed using the Hann function. Resulting time-domain signals are transformed into the frequency domain and magnitudes are isolated. The resultant magnitude spectrum is then filtered using a zero-phase, equiripple FIR filter with 5% cutoff frequency, to smooth the resultant magnitude spectrum without causing resonant peak shift. Once this filtered spectrum is produced, finding resonant peak frequency is accomplished by searching for a global maximum.

In this research, four different volumes were used with primary resonant frequencies of 335 Hz, 400 Hz, 635 Hz, and 995 Hz for large, medium, small, and very small resonator volumes, respectively. Each volume was excited using an impinging jet flow at zero degree angle and 0.5 cm distance. In Fig. 2, a time domain acoustic signal and a spectral decomposition are presented, as measured. Readily visible is a large-scale resonant structure, which has been corrupted with broad spectrum noise. Additionally, resonant structure is unstable in time; a non-stationary peak frequency is observed.

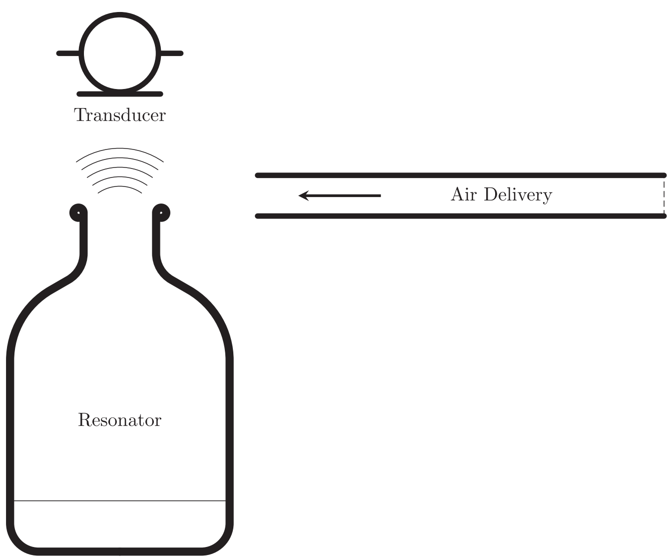

Fig. 1. Acoustic resonator and measurement system diagram. Drawing representative of general hardware but not shown to scale. Air is delivered externally and passed over resonator opening. Acoustic resonance signals are transduced and recorded using a microphone and analog-to-digital converter.