ABSTRACT

In this study we evaluate the feasibility of using a simple, unstabilized, homodyne interferometer configuration for local wavenumber estimation of guided waves, a process known as acoustic wavenumber spectroscopy [1]. Acoustic wavenumber spectroscopy identifies damage in a two-dimensional scan on a pixel by pixel basis, by estimating the wavenumber of a structure's response to a steady-state, single frequency, ultrasonic excitation. By leveraging the requirement to measure only a single known frequency it may be possible to use a simplified laser doppler vibrometer (LDV). A simple and inexpensive laser ultrasound scanning device would provide convenient and rapid stand-off inspection for evaluating structural damage in a variety of settings. Due to the typical cost, complexity, and size of commercial LDV systems, they are often only used for one-off measurements in the laboratory. A simplified system could enable permanent deployment of LDV technology for persistent structural health monitoring applications.

INTRODUCTION

Laser Doppler Vibrometry provides a convenient, rapid, stand-off inspection method for analyzing vibrations in a variety of situations. To make a measurement, a Laser Doppler Vibrometer splits a laser into a target and reference beam. After the target beam reflects off the sample, it is then recombined with the reference beam to produce an interference pattern, a process known as interferometry. Common interferometer designs include homodyne and heterodyne configurations, both of which can yield an electrical output proportional to the sine of the optical phase shift created by displacement of a sample surface. The addition of a bragg cell in the heterodyne configuration is the significant difference between the two arrangements.

Most commercial LDV systems utilize a heterodyne interferometer configuration as shown in figure 1. Compared to the homodyne configuration shown in figure 2, the heterodyne arrangement provides greater isolation from

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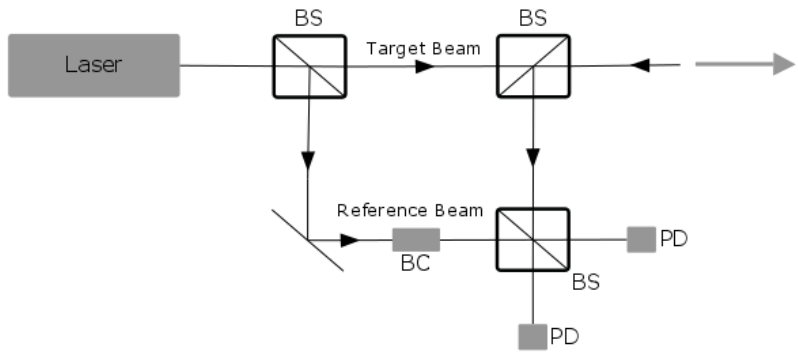

Figure 1. Heterodyne configuration. BC is bragg cell, BS is beam splitter, and PD is photodetector.

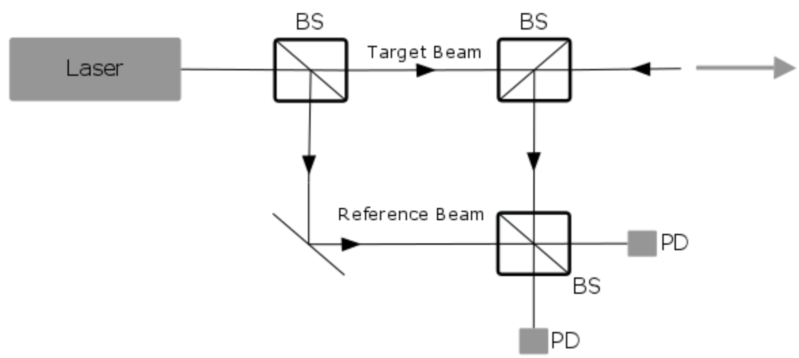

Figure 2. Homodyne interferometer configuration.

environmental vibrations, and variations in the reflected light intensity [2]. The advantages of the heterodyne configuration come at the expense of increased complexity of the optical configuration and electronics used for signal processing, as well as increased system size, in addition to a greater system cost.

In acoustic wavenumber spectroscopy we perform structural imaging through estimation of the local wavenumber of guided waves by subjecting a structure to a steady, single-tone excitation. In a given material the wavenumber of a wave at a given frequency is a function of the geometry and material properties of that material [3]. As damage often changes these properties, changes in local wavenumber can be used as indicators of damage. Using steady-state waves provides the benefit of higher surface wave displacement, requires no delay between measurements, and a few wave cycles are adequate to evaluate the wave behavior at each scan point [4]. By leveraging the requirement to only measure the relative amplitude and phase of waves at a single, known temporal frequency, the size and complexity of our custom laser vibrometer can be reduced compared to existing commercial LDV's. Additionally, in acoustic wavenumber spectroscopy, the excitation source is fixed at an arbitrary location, and the location does not affect the imaging so long as energy reaches the inspection region. This insensitivity to excitation source also contributes to the overall simplicity of our custom laser vibrometer.

METHODS and MATERIALS

Laser Vibrometer Elements

The scanner technology consists of four components; the excitation package, the optics package, and the electronics and digital signal processing package. The excitation package consists of an ultrasonic transducer, and the amplifier required to drive the transducer, while a 1550 *nm* laser diode, the laser diode driver, and a dual-axis, scanning galvo mirror system, comprise the optics package. The system is entirely composed of fiber optic components. A National Instruments data acquisition system digitizes the photodetector signal and controls the dual-axis scanning mirrors, allowing adjustments of scan area, position, and scanning speed. Figure 3 shows a conceptual layout of the system.

Scanning Procedure

When a scan is conducted the transducer continuously produces a single tone ultrasonic excitation frequency for the duration of the scan, in order to produce a steady state response in the structure. The laser then sweeps over the 2D scan area, and the photodetector outputs are digitized and saved as two streams of values. The collected data vectors are then summed and broken into equal sized blocks and saved as a 3D matrix, *V(x,y,T)*. The size of the blocks depends on the desired pixel size, and the scan speed. The inner product is then taken along the time dimension according to,

$$c(x,y) = \frac{1}{T}\sum_{t=0}^{T} V(x,y,t) * \exp(-j2\pi f_e t), \tag{1}$$

where f_e is the excitation frequency. The complex valued matrix $c(x,y)$ contains the relevant response information. The complex valued matrix is then processed to produce the final wavenumber map using techniques detailed in [1].

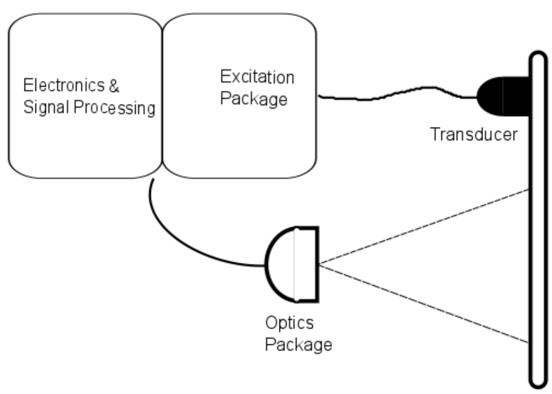

Figure 3. Conceptual drawing of the custom laser doppler vibrometer.

RESULTS and ANALYSIS

Signal Processing

When the guided wave amplitude is small compared to the laser wavelength (approximately $\frac{1}{8}\lambda$) [5], a homodyne interferometer will output an ideal signal of the form,

$$V = \cos\left(\frac{4\pi}{\lambda} Bsin(\omega_e t)\right), \tag{2}$$

where ω_e is the angular excitation frequency, λ is the laser wavelength, and B is the vibration amplitude. In our case, with the presence of external environmental vibrations and the motion of the mirrors, the acquired signal is considerably more complex.

A typical frequency spectrum resulting from a scan displays the excitation frequency and subsequent harmonics, with sidebands whose frequency is proportional to the scan speed. Figure 4 displays a typical frequency spectrum resulting from a scan. The sidebands seen in the spectrum are likely an additional doppler shift induced by the motion of the mirrors. Equation 2 must be modified to account for the additional doppler shift due to the mirror movement, similar to the additional bragg frequency that is present in a heterodyne signal. The modified signal also includes an amplitude modulation term.

Equation 3 produces a frequency spectrum similar to what we see from experimental data.

$$V = \sin(\omega_m t)\left[\cos\big(\omega_m t + \phi(t)\big) + \sin\big(\omega_m t + \phi(t)\big)\right], \tag{3}$$

where $\phi(t) = \frac{4\pi}{\lambda} Bsin(\omega_e t)$, and ω_m is the apparent doppler shift due to the mirror motion. Figure 5 shows that the frequency spectrum produced from equation 3 reproduces the major frequency components seen in data we collected from multiple scans.

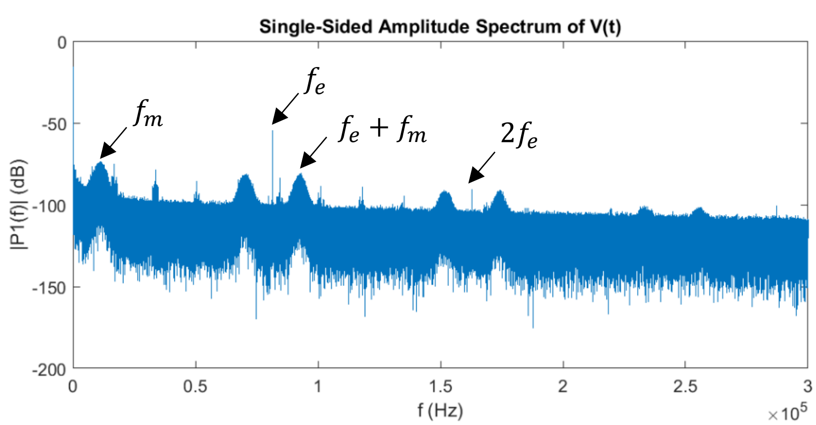

Figure 4. Typical scan spectrum; f_e is the excitation frequency, f_m is proportional to the scan speed.

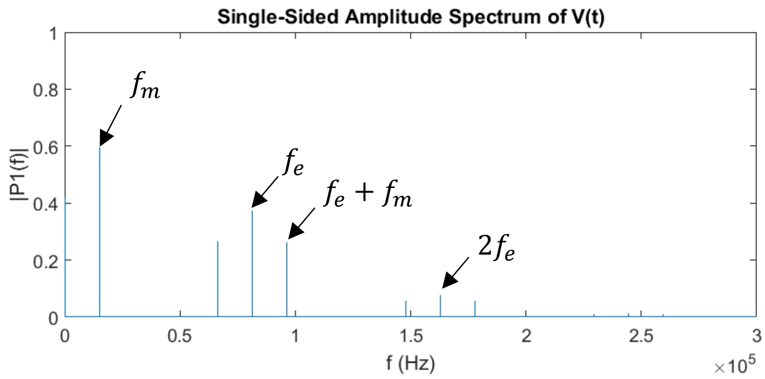

Figure 5. Frequency spectrum produced from the simulated signal, equation 3.

It is likely then, that the signals collected from our vibrometer have a form similar to equation 3. The challenge is to extract the relevant vibration information, $\phi(t)$. Equation 3 exhibits some similarities with a heterodyne signal which has the form,

$$V = A\cos\left(\omega_b t + \frac{4\pi}{\lambda} B\sin(\omega_e t)\right), \tag{4}$$

where ω_b is the frequency shift produced by the bragg cell, and ω_e is the excitation frequency. It may be possible to take advantage of this similarity, and use a modified heterodyne demodulation technique to isolate the structure response, $\phi(t)$. Without demodulating the acquired signal to remove the apparent doppler shift due to the galvo mirror motion, we have still successfully imaged defects in an aluminum plate. However, scan quality and resolution will improve if the acquired signals are successfully demodulated.

Preliminary Tests

We successfully imaged guided waves in aluminum plates by analyzing the magnitude of the complex valued matrix, $c(x, y)$, from equation 1.

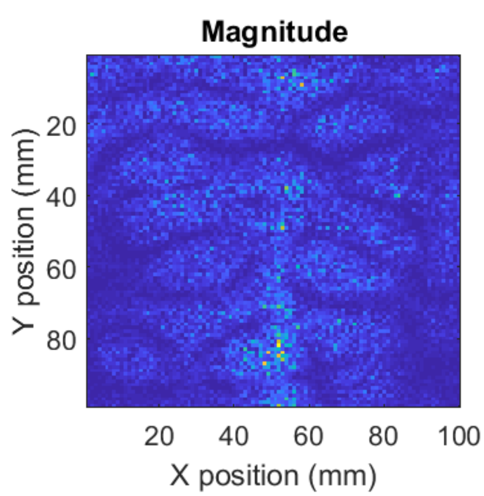

Figure 6. Wave pattern apparent in measured response magnitude.

Figure 6 shows a visible wave pattern detected on a 3 *mm* thick plate, with a scan area of 100 cm^2. In areas where thickness is reduced, the response of the plate is increased, and the increased response can be detected, and the change in wavenumber can be identified. Further scans on an additional plate revealed a small, 0.74 *mm* deep milled area, by visually inspecting the response magnitude, without any additional signal processing using acoustic wavenumber spectroscopy techniques. This scan image is featured in figure 7. With further processing it should be possible to further isolate and highlight the thin section. The plate itself, with the milled thin area, is shown in figure 8.

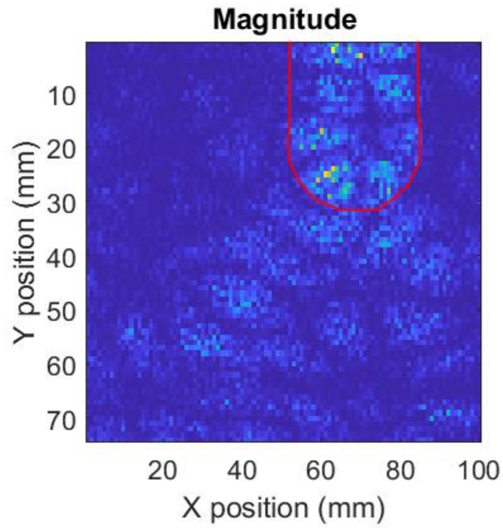

Figure 7. Thinning (red outline) apparent in the wave pattern.

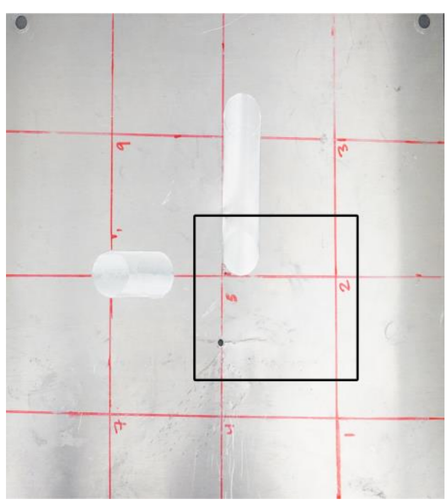

Figure 8. Sample aluminum plate. The black box indicates the scan area displayed in figure 7.

CONCLUSION

We investigated the possibility of using an unstabilized, simplified version of a homodyne vibrometer to image defects in plate like structures through acoustic wavenumber spectroscopy. We showed that the signals collected from the simplified vibrometer contain information pertaining to the response of a structure to steady-state ultrasonic excitation, and that the magnitude of the structure response to steady-state excitation can be used to image defects without demodulation or further processing. Further, we made progress in simulating a signal that is an adequate representation of the experimental data, in order to develop a demodulation algorithm for extraction of the unmodulated structure response, which will allow us to produce scans with higher resolution. An added benefit of our custom LDV, besides simplicity and compactness, is the significantly reduced cost compared to many current commercial systems.

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