MICROWAVE INTERFEROMETER FOR NON-DESTRUCTIVE TESTING

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ABSTRACT. A K-band microwave interferometer for non-destructive sensing of high frequency low amplitude (nm) vibration is demonstrated. This sensor uses direct-conversion receiver architecture with a phase shifter to adjust its sensitivity while varying the target distance. Detection of nanoscale vibration and laser-generated ultrasound waves through thin aluminum plate are measured and then compared with the theoretical results.

Keywords: Microwave Interferometer, Laser Generated Ultrasonic, Noncontact, Nondestructive, Lamb Wave
PACS: 07.57.-c; 42.25.Hz; 81.70.Ex

INTRODUCTION

In this paper, the technical feasibility of a microwave interferometer coupled with a pulsed laser for multi-purpose Non-Destructive Evaluation (NDE) is presented. Fast, reliable, and noncontact inspection of structural health is of great interest in many industries. Currently, space transportation vehicles, civilian airlines and military air units are faced with increased safety concerns as fleets age. As the duration and frequency of missions or services increases, and remain in service for longer period of time, more inspections will need to be performed in order to monitor the aging process of the structure and to ensure its integrity. For this purpose, NDE equipment that is compact, lightweight, easy to use, and that exhibits low power consumption is required. A flexible, remote, and non-contact inspection technique can improve component reliability and safety and can identify errors in processes early enough to avoid significant levels of rejected parts.

Although microwave interferometers based on direct-conversion or homodyne architecture have been researched and utilized for detection of vibrating objects in different fields and applications [1]-[4], its advantages have not been fully utilized in the field of nondestructive testing. Currently, the most commonly used noncontact detection device for ultrasonic waves is the laser interferometer. Despite the high signal-to-noise ratio, small footprint resolution, low noise equivalent surface displacement, etc., laser interferometers suffer from the following limitations: 1) inability to work in factory

CP1211, *Review of Quantitative Nondestructive Evaluation Vol.29,*
edited by D. O. Thompson and D. E. Chimenti

environment where thermal, mechanical and optical propagation (such as fumes, water drops, etc.) perturbations are present; 2) reduction in sensitivity caused by the speckle nature of the light reflected from rough surfaces; 3) high system cost due to the price of the probe lasers and 4) high maintenance cost. Microwave interferometers may be a suitable alternative for ultrasonic wave detection that can overcome these limitations.

The usefulness of a microwave interferometer coupled with a pulse laser generator is not limited to only structural health diagnosis or defect detection, but can also serve in determining the target's material properties. For example, the thickness of the thin metal plate sample can be determined remotely by plotting the dispersion curve of the lamb wave from the measured data. This example is also discussed in this paper.

PRINCIPLE OF OPERATION

Microwave Interferometer

For the target with periodically varying displacement, the interferometer acquires the target information through demodulation of the backscattered signal by mixing with the reference signal synchronized with the carrier frequency of the signal reflected off the target. A vibrating target will modulate the phase of the carrier signal in proportion to the time varying target location

$$\phi(t) = \frac{4\pi x(t)}{\lambda}. \tag{1}$$

If the displacement of the target is small compared to the wavelength of the carrier signal, demodulating this phase will produce a baseband signal proportional to the target displacement. In the ideal system where amplitude variations are neglected, a continuous wave source typically transmits a single-tone signal

$$T(t) = \cos(2\pi f t) \tag{2}$$

where f is the oscillation frequency. The directional coupler splits this signal into the reference LO signal and the RF signal that radiates through the open-ended waveguide.

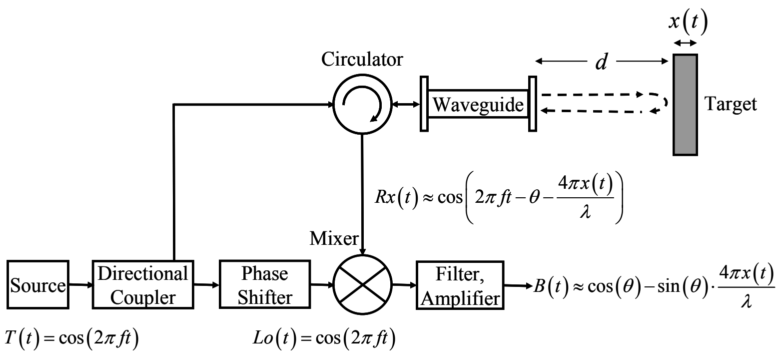

FIGURE 1. A block diagram of an ideal microwave interferometer for non-destructive testing.

When the backscattered signal $Rx(t)$ is multiplied or mixed with the reference signal $Lo(t)$ as shown in Fig. 1, the resulting low-pass filtered baseband signal will be composed of DC and AC voltages

$$B(t) = Rx(t) \cdot Lo(t) = \cos(\theta) - \sin(\theta) \cdot \phi(t) \tag{3}$$

where the first and second terms relate to the baseband DC and AC voltages, respectively. Small angle approximation is used to extract the time-varying phase content $\phi(t)$ and

$$\theta = \theta(d) + \Delta\theta \tag{4}$$

is the phase difference between the two input ports of the mixer. $\theta(d)$ is the constant phase shift dependent on the nominal distance between the detector and the target (d), $\Delta\theta$ is the phase different introduced between the two input ports of the mixers caused by several factors excluding $\theta(d)$ such as the difference in the electrical length between the LO and Rx paths and reflection from the target surface, and $\phi(t)$ is the time-dependent phase variation produced by the vibrating motion of the sample [1]. In the ideal case, the AC voltage which carries the target information can be maximized at any target distance by adjusting the DC voltage to zero. According to (3), the highest AC voltage is produced when θ is an odd multiple of $\pi/2$. Two simple techniques to set the system to its optimum region are by either placing the target at the optimum target distance or by manipulating $\Delta\theta$ using the phase-shifter.

In the non-ideal case however, the undesired DC offsetting will manifest due to either hardware imperfection or undesired reflections within the system [5, 6]. For example, if there is a relatively large reflection from the open-ended waveguide, this undesired signal will be added to the desired backscatter signal from the target before being downconverted through the mixer. This undesired DC offset is shown in the first part of (5). It is this extra DC term that will prohibit the continuous optimization of the system using the phase shifter for all target distances.

$$B(t) = \cos(\Delta\theta) + \cos(\theta(d) + \Delta\theta) - \sin(\theta(d) + \Delta\theta) \cdot \phi(t) \tag{5}$$

Laser-Based Ultrasound Generation

Laser ultrasonic is a modification of the conventional transducer-based contact ultrasonic inspection. Instead of a transducer, a pulse laser is used to generate the ultrasound wave. Ultrasonic waves are associated with elastic wave motion whose particle motions are governed by a set of longitudinal and shear wave equations subject to boundary conditions representing the structural geometry. For a stress free thin plate, such as the sample used in this experiment, lamb waves will propagate through the medium. Given the material properties and the thickness of the sample, the dispersion curve of the lamb wave can be numerically plotted [7]-[9] as shown in Fig. 2. Lamb wave dispersion curves are used to describe the relationship between frequency, phase velocity, mode, and thickness of the sample. In most cases, ultrasound induced by the pulse laser generates a transient surface displacement in the nanometer scale for a compressional wave (It is usually larger for surface waves). The microwave interferometer is used to detect the resulting nanoscale displacement produced by the transversely traveling lamb waves.

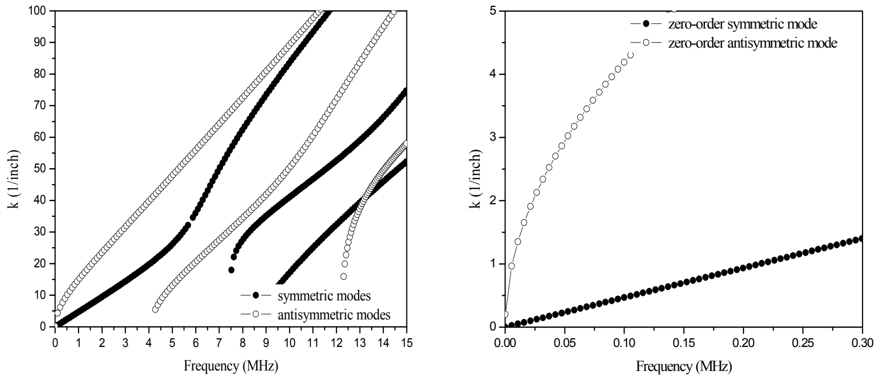

FIGURE 2. Numerically computed lamb wave dispersion curve for aluminum plate with thickness = 381um. LEFT: first three symmetric and antisymmetic lamb wave modes (S0, S1, S2, A0, A1, and A2). RIGHT: zero-order lamb wave modes below 0.3MHz.

Unlike transducer-based systems, laser ultrasound is remote, thus allowing inspection of moving parts, at high temperature or in hazardous environments.

EXPERIMENTAL SETUP

Two types of experiments are carried out to verify the feasibility of using a K-band microwave interferometer for Non-Destructive Testing (NDT) applications. First, detection of nanoscale vibration is examined to test the capability of this sensor in detecting small displacement variation of the target. Second, the interferometer is used to detect laser generated ultrasonic waves.

Experimental Setup for Detection of Nanoscale Vibration

The K-band was chosen for the prototype over other spectrum bands for the following reasons: First, the modulated phase in the baseband $\phi(t)$ is inversely proportional to the wavelength of the carrier signal. Therefore for the same target displacement, operating at a higher frequency with shorter wavelength will generate a larger phase modulation [2]. Second, this short wavelength further enables the use of smaller components which reduce the overall system dimension. Lastly, the K-band spectrum is widely used for commercial Doppler radar systems therefore finding low cost components is relatively easy compared to higher frequency bands. For these reasons, widely available high microwave frequency components in the K-band are used to build our interferometer. A Gunn diode with output power of 20dBm is used to make the system portable and to provide enough power to drive the mixer. For the detector (or field sensor), a rectangular waveguide is used to produce a more uniform and relatively higher footprint resolution on the surface of the target. The radiated power at the output of the waveguide detector is 0dBm.

The nanoscale vibration of the target is produced by attaching a small piece of metal onto a piezoelectric actuator which is connected to a waveform generator. Target displacement and vibration frequency are adjusted by changing the output voltage and frequency of the waveform generator. The target frequency is set to 88.7MHz and the displacement is varied in the nanoscale range. The target is mounted on a translation stage which is controlled by LABVIEW for precise target distance adjustment. A system with a feed-back circuit is also assembled to enable the system to self-adjust to the optimum region not only at some specific locations but within some range of target distance. However, due to the undesired DC offsetting and attenuations factors, the target needs to be placed in close proximity from the detector. A voltage controlled phase shifter is used in our prototype to automate the DC adjustment.

Experimental Setup for Detection of Ultrasonic Wave

Our innovative sensor is based on the integration of a microwave interferometer coupled with a pulsed laser that generates the ultrasonic wave as shown in Fig. 3. For the laser source, a pulse of 5ns duration and 200mJ energy is used to generate plane ultrasonic waves. The detector is placed at some distance away from the laser source then moved up to the source point with small increments. The distance between the detector and the source, and time of arrival of the ultrasonic waves are measured and then recorded in the baseband. The footprint resolution of the rectangular waveguide with the target placed about 2mm away from the detector is ≈ 5mm, which limits the maximum detectable frequency in the low frequency region to under megahertz range. In this region only zero-order symmetric and antisymmetric modes propagate.

RESULTS

Nanoscale Vibration Results

The detection of around 330nm and 100nm peak-to-peak vibration is successfully detected using the microwave interferometer. If the target can be placed at specific

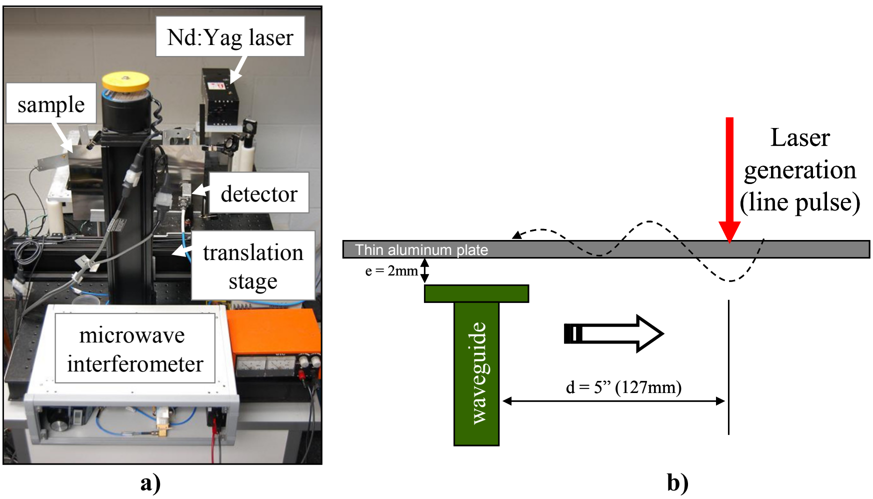

FIGURE 3. a) Measurement setup of microwave interferometer with laser backed generation on the sample place in between the detector and the source. b) Diagram of the data collection setup.

locations, the optimum target distance can be found from the voltage vs. target distance scan. The optimum target distance is where the maximum AC root-mean-squared (V_{rms}) values are measured as illustrated in Fig. 4. In general, the baseband signal can be set to its optimum region if the path difference between the LO and Rx signals are maintained where the interferometer response stays in the linear region or if the target is placed in the region where the slope of the DC curve is maximum. Without placing the target in front of the detector, the phase shifter is adjusted to eliminate the DC offset prior to scan to avoid the corruption or saturation of the baseband signal. The measured results using the feedback system is shown in Fig. 5. Using the voltage-controlled phase shifter, our system is able to self adjust to its optimum region up to about 2.5mm of target distance.

The calculated signal to noise ratio in the baseband with the low-pass filter (f_c = 200kHz) is about 11dB and the minimum detectable displacement is 27nm. The noise equivalent surface displacement (NESD) value is 0.06nm/√Hz. The signal to noise ratio and NESD values can be further improved by optimizing the system architecture, using lower noise figure components, removing undesired DC offset in the baseband, etc.

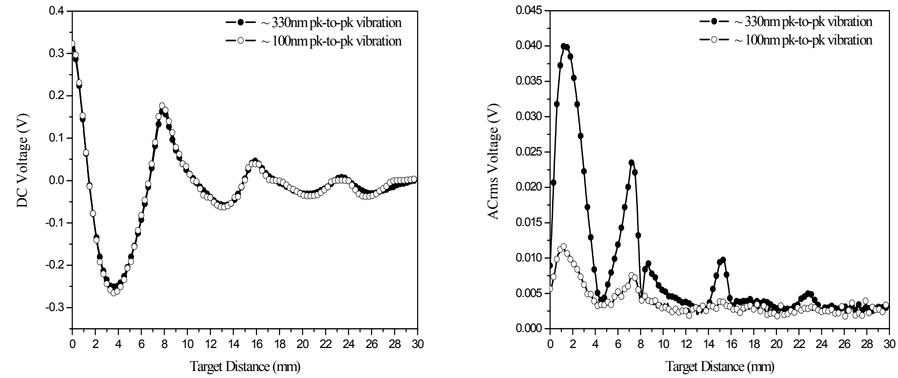

FIGURE 4. Baseband DC and AC_{rms} voltages vs. target distance for different target peak-to-peak vibration displacements (~330nm and ~100nm pk-to-pk target vibration).

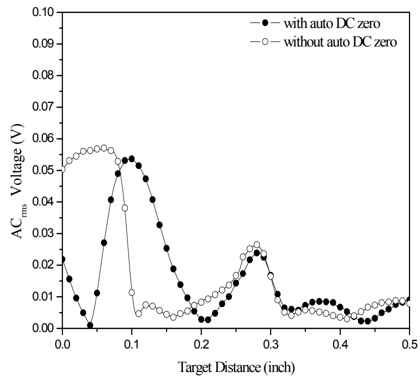

FIGURE 5. Baseband AC_{rms} voltage: with and without the automatic DC-adjustment feedback circuit.

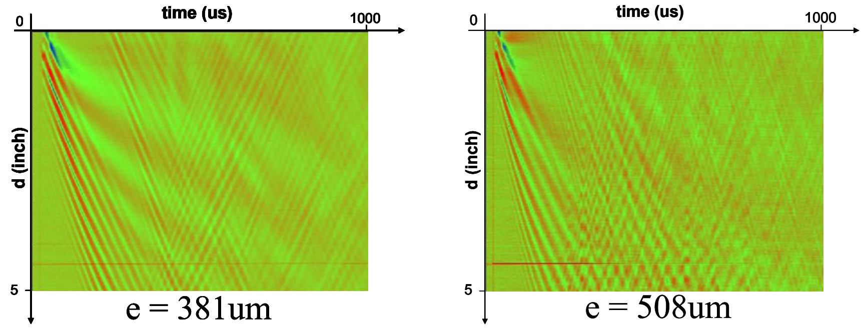

FIGURE 6. Measured B-scan for different aluminum plate thicknesses.

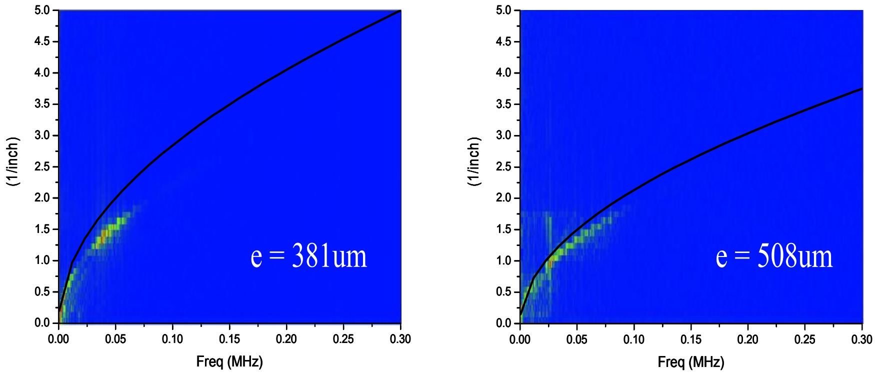

FIGURE 7. Measured vs. Theoretical lamb wave dispersion curves for different aluminum plate thicknesses (zero-order antisymmetric mode).

Ultrasonic Detection Results

The measured results for laser generated ultrasonic waves in thin aluminum plates with different thicknesses are shown in Fig. 6. The y-axis is the distance between the detector and the laser source point, x-axis is the detection time of the ultrasonic wave for each distance. The ability to detect these acoustic waves allows the system to perform 2D image mapping of the sample to locate the defect in the structure. The Fourier transformed measured results and the numerical results show good agreement between the two dispersion characteristics for different aluminum plate thicknesses (Fig. 7). Different sample thicknesses exhibit unique dispersion curves; therefore a possible application is to remotely determine the thickness of the sample without any prior knowledge. Only antisymmetric modes are visible in the measured results because the laser pulse is applied to only one side of the sample which couples most of the energy to the antisymmetric mode.

CONCLUSION

Microwave interferometer based on the homodyne topology is a promising tool in the field of non-destructive testing. Nanoscale vibration and ultrasonic waves are successfully measured then compared to the theoretical results using a microwave interferometer coupled with a laser pulse source. This demonstrates a completely noncontact testing system that can be used in various applications, for example in detecting defects or determining target properties. Its advantages such as low-cost, portability, ability to detect small displacements and to penetrate through dielectric walls sets it apart from conventional sensors including laser interferometer.

ACKNOWLEDGEMENTS

This research is supported by NASA. The authors thank Bruno Pouet of Bossa Nova Technologies for helpful discussions.

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