System Model for MEMS based Laser Ultrasonic Receiver

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ABSTRACT

A need has been identified for more advanced nondestructive Evaluation technologies for assuring the integrity of airframe structures, wiring, etc. Laser ultrasonic inspection instruments have been shown to detect flaws in structures. However, these instruments are generally too bulky to be used in the confined spaces that are typical of aerospace vehicles. Microsystems technology is one key to reducing the size of current instruments and enabling increased inspection coverage in areas that were previously inaccessible due to instrument size and weight.

This paper investigates the system modeling of a Micro OptoElectroMechanical System (MOEMS) based laser ultrasonic receiver. The system model is constructed in software using MATLAB's dynamical simulator, Simulink. The optical components are modeled using geometrical matrix methods and include some image processing. The system model includes a test bench which simulates input stimuli and models the behavior of the material under test.

Keywords: Modeling, MOEMS, Geometrical Optics, MicroOptoElectroMechanical Devices, Image Processing, MEMS, MicroElectroMechanical Devices,.

1 INTRODUCTION

The rapid growth in air traffic and the continuing presence of vehicles being operated beyond the design cycle has exposed the need for more advanced Nondestructive Evaluation (NDE) technologies for assuring integrity of airframe structures, wiring, etc. Laser ultrasonic inspection instruments have been shown to be attractive for detecting fatigue cracks and delaminations in structures [1]. However, laser based inspection instruments are generally too bulky to be used in small confined spaces that are typical of today's aerospace vehicles. Micro Electro-Mechanical Systems (MEMS) are a key technology to miniaturizing this type of instrument. Reducing the size of current instruments by a factor of 10^3 will enable increased inspection coverage in areas that were previously inaccessible due to instrument size. Using standard MEMS fabrication techniques, a Micro OptoElectroMechanical System (MOEMS) is being developed for aerospace applications. This system will allow for rapid, remote, and automated NDE for vehicle health monitoring.

This paper describes the system modeling of a MOEMS based Laser Ultrasonic Receiver (LUR) system. See Figure 3 for a block diagram of the laser ultrasonic receiver system. The LUR system is comprised of a laser which reflects a beam off of a material in which ultrasonic waves have been created, and an optical system that detects the ultrasonic waves. The laser beam interacts with induced ultrasonic waves creating a reflected beam that is ultrasonically modulated. The micro-optical components direct the reflected beam to a detector where the beam is combined with a reference beam to demodulate the ultrasonic signal. The photo-emf detector [2] outputs an analog signal that is proportional to the velocity of the ultrasonic waves. Analysis of the received signal is used to establish the integrity of the material.

The system model is constructed using MATLAB's dynamical simulator, Simulink. The model employs a top down design approach which hierarchically breaks down the LUR system into manageable components. Each optical component is modeled using matrix geometrical optic methods and includes some image processing. The optical models employ geometrical system matrices for calculations involving the focus and magnification factor. Each component is passed both an image for dynamical manipulation and a state vector.

The system model includes a test bench which simulates input stimuli and models the behavior of the material under test conditions. The optical components modeled include: thick lenses, mirrors, a beam splitter, wave plates, and the detector. The wave plates are modeled using rotational matrices, while the other optical components incorporate paraxial matrix methods. Other effects taken into account in the system model are the optical losses incurred due to etch-hole size and spacing. The purpose of the system model is not only to determine the feasibility of design but also to identify which components and component parameters are critical for achieving the design specifications.

2 MODELING APPROACH

The modeling approach uses top down design methodology to decompose the laser ultrasonic receiver system into a hierarchy of sub-components. A hybrid approach involving both geometrical matrix optical modeling and image processing is used to model the optical components of the MOEMS based laser ultrasonic receiver. The modeling is performed by MATLAB'S dynamical simulator, Simulink. Both an image and a state vector are passed to each component. The state vector is comprised of the following information: paraxial angle, paraxial height, phase angle, direction angle x, direction angle y, Direction angle z, distance from preceding element, height of beam plane, and width of beam plane. Geometrical matrices are calculated for each component and used to modify the image dynamically. This information is used to calculate the modifications to the image and the new state vector that is passed on to the next component.

3 MODELING TECHNIQUE

3.1 Geometrical Matrices

Geometrical matrix optical modeling techniques are based upon the paraxial assumptions, which state that the angles involved with a ray trace must be close to zero [3]. Put another way, the angles must be very close to parallel to the optical axis. This eliminates the use of trigonometric functions since sin (θ) ~ θ, and cos (θ) ~ 1, for very small values of θ. Removal of the trigonometric functions allows the tracing of rays to be accomplished using simple matrix manipulations. For example (See Figure 1), if a ray translates a distance t_1, through a medium with index of refraction n_1, starting with height h, and the ray has an initial angle θ, then the new height h_1, and new angle θ_1, can be calculated using the following matrix equation:

$$\begin{pmatrix} \theta_1 \\ h_1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{t_1}{n_1} & 1 \end{pmatrix} \bullet \begin{pmatrix} \theta \\ h \end{pmatrix}. \qquad (1)$$

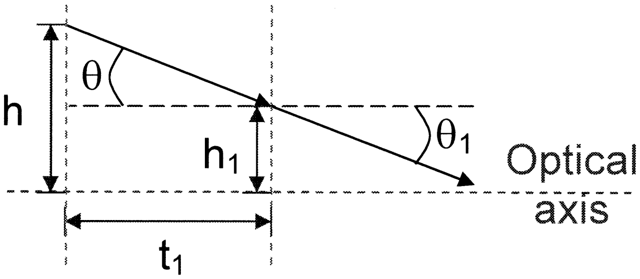

Figure 1: Geometry of a ray translation.

Besides translation matrices, there are matrices for both refractive and reflective phenomena. These three types of matrices comprise the basic set of building blocks that can be used to develop system matrices for almost all optical components [4].

3.2 Component Modeling using Geometrical Matrices

Models for optical components can be developed using the three basic building blocks just discussed. The blocks are simply multiplied together to create system matrices for the components. Each component's system matrix is used in the simulation by multiplying it by a subset of the current state matrix, to come up with new parameters for the new state matrix [5]. The general equation used to calculate the new parameters is

$$\begin{pmatrix} \theta_1 \\ h_1 \end{pmatrix} = \begin{pmatrix} System \\ Matrix \end{pmatrix} \bullet \begin{pmatrix} \theta \\ h \end{pmatrix}. \qquad (4)$$

3.3 Other Modeling Techniques

In addition to geometrical matrix optical modeling our application drove us to investigate Etch hole modeling and image processing. In the future mechanical and electrical parameters will be added to the component models.

3.3.1. Etch Hole Modeling

Many MOEMS devices are required to have holes etched so that the release etchant can flow under the device and insure the complete removal of a sacrificial layer. This allows moving parts to be free from any substrate or unwanted attachments. Because etch holes have a large effect on the reflectivity of MOEMS mirrors they have been included in the models. Using data from [6], and lookup tables in Simulink, a block has been developed that takes into account etch-hole size and spacing, as well as the angle of the mirror when determining the intensity of light that is reflected from a MOEMS mirror.

3.3.2. Image Processing:

Simulink is a dynamical simulator and as such can perform image processing using plane waves in conjunction with the geometrical matrix modeling. Matlab's Image toolbox can be used for manipulating an image, under the control of the LUR system model components. Functions such as resizing of images, image intensity scaling, and others can be modified under the direction of the optical components discussed.

4 SYSTEM MODEL OF A MOEMS LASER ULTRASONIC RECEIVER SYSTEM

This paper investigates the system modeling of a MOEMS based Laser Ultrasonic Receiver (LUR) system. This type of laser ultrasonic receiver is comprised of a laser and an optical system that detects the ultrasonic waves. The laser beam is reflected off a material in which ultrasonic waves have been created. The laser beam interacts with induced ultrasonic waves creating a reflected beam that is ultrasonically modulated. This reflected beam is directed by the micro-optical components to a photo-emf detector where the beam is combined with a reference beam to demodulate the ultrasonic signal [7]. The photo-emf detector outputs a signal that is proportional to the amplitude and phase of the ultrasonic waves. Material integrity is established by analysis of the demodulated signal.

The ultrasonic waves can be created by using a second laser that fires a short, intense pulse of light onto the material under evaluation. The ultrasonic waves are induced by rapid local heating that takes place in the material due to the laser pulse [8]. It is these ultrasonic waves that are detected by the LUR system.

The entire laser ultrasonic receiver system is modeled hierarchically using Simulink. The optical subsystem (Figure 4) is one of many blocks and uses the geometrical system matrices to model the optical performance of the MOEMS components. The optical system is divided into three paths; a transmission beam path on top, a reference beam path, and a modulated beam path shown on the bottom of Figure 4. The transmission path has two inputs found on the upper left side of the diagram, the state vector, and an image of the initial laser beam plane wave. The laser beam is passed through a mirror and a phase shifting wave plate before entering the beam splitter. The reflected beam from the beam splitter becomes the transmission beam. The transmission beam path passes through a lens to another wave plate, to a second lens, and finally through a mirror and out as both an image and as a state vector. Both of which are sent to the material under test.

The reference beam comes from the beam splitter. It is the transmitted beam from the beam splitter. The reference beam is passed to a mirror where it is redirected to the detector. This beam is necessary for demodulating the analog signal. The demodulation is accomplished by destructive interference between the reference beam and the modulated beam [9].

The lower set of inputs on the right side of the diagram represents the modulated beam path. This path begins with the transmission beam after it has reflected off of the material under test. In this design the beam must retrace through the optical path to reach the detector. At the detector both the reference beam and the modulated beam are summed destructively to generate an analog signal. Figure 2 is a plot of the reference beam (top trace), the reflected measurement beam (middle trace), and the analog signal generated by the detector (bottom trace). All three traces are modeled as plane waves in the LUR system model. The detector signal clearly shows the initial ultrasound pulse created within the material. It also shows the second pulse that is reflected from the back side of the material or a discontinuity within the material. By analyzing the time of flight between the two pulses a determination can be made about the integrity of the material under test.

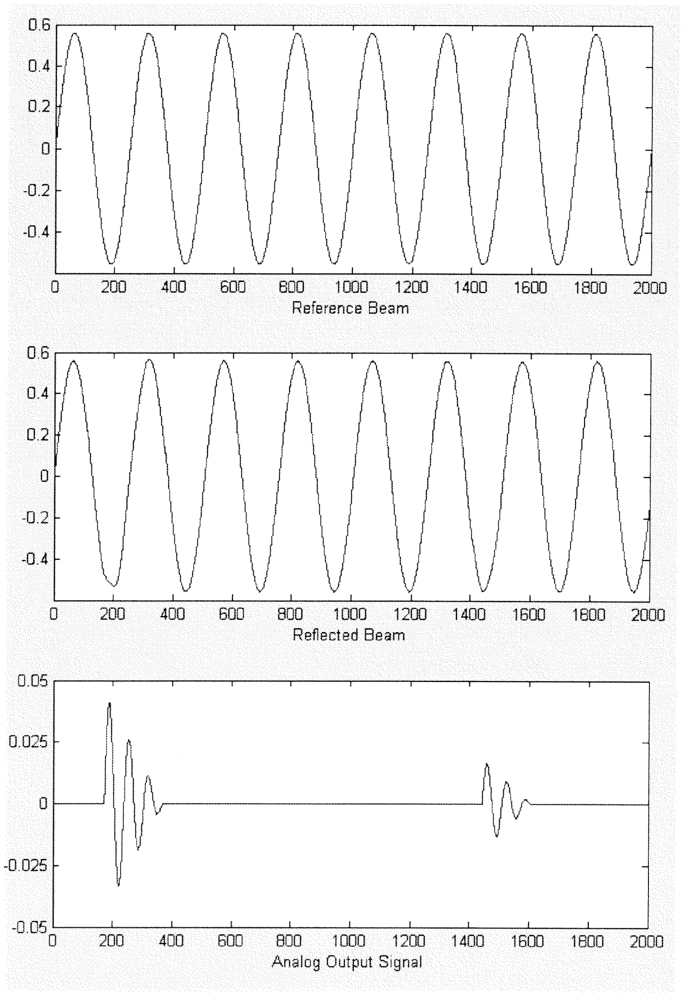

Figure 2: Plot of the laser ultrasonic receiver signals; the reference beam (top), the reflected beam (middle), and the analog signal generated by the detector (bottom).

CONCLUSION

A system model for a Laser Ultrasonic Receiver System has been developed. The system model includes geometrical matrix modeling of MOEMS components and image processing. A software test bench which simulates input stimuli and models the behavior of the material under test conditions has also been developed. The optical components modeled include: thick lenses, mirrors, a beam splitter, wave plates, and the detector. The modeling is performed by MATLAB'S dynamical simulator, Simulink.

In the future we plan on adding diffractive optical components as well as electrical and mechanical components. We also hope to fabricate the laser ultrasonic receiver system to verify the simulation results generated by our system model. Should this work be successful it will enable increased NDE inspection coverage of aerospace vehicles in areas that were previously inaccessible due to instrument size and weight.

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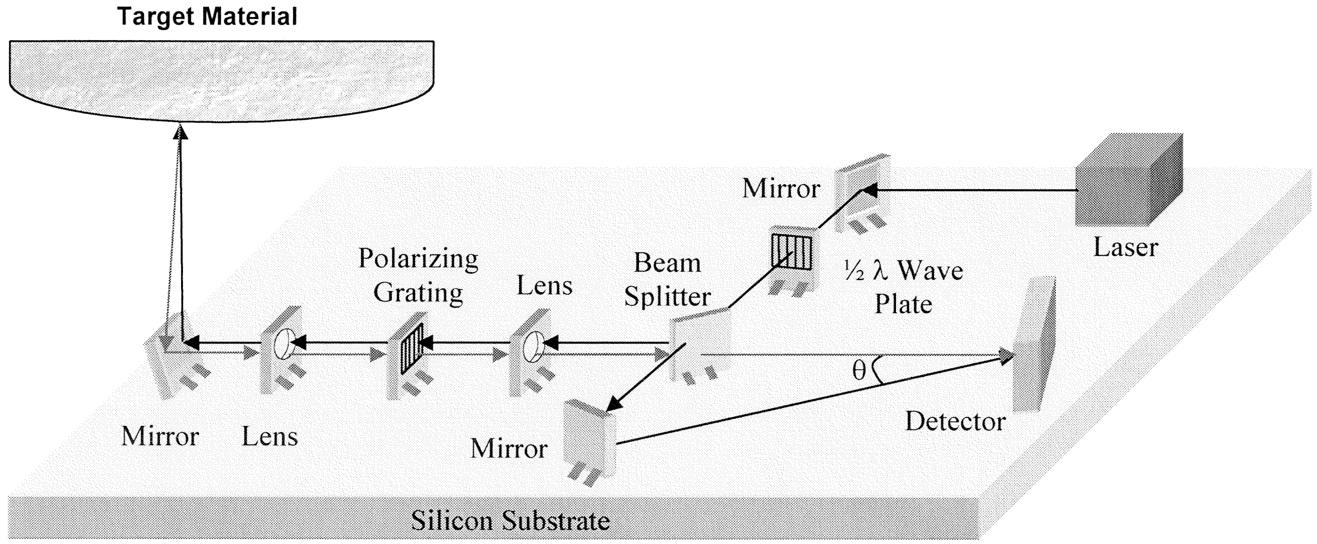

Figure 3: Block Diagram of MOEMS based Laser Ultrasonic Receiver system.

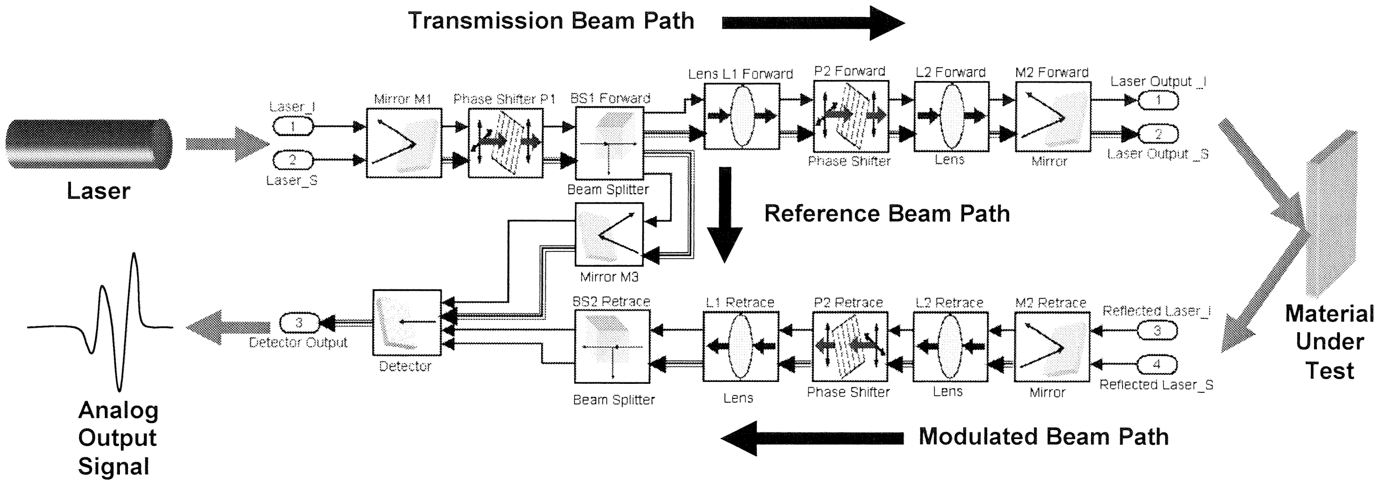

Figure 4: Block Diagram of Optical Subsystem.