MODELING AND IMAGING FLEXURAL PLATE WAVE DEVICES

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ABSTRACT

Sandia National Laboratories is developing a new form of flexural plate wave device (FPW) for sensor applications. In this device, Lorentz forces cause out of plane vibrations in a silicon nitride membrane. Current induced in transducer lines on the membrane provides information about the amplitude and phase of these surface vibrations. By tracking the large amplitude vibrations that occur at resonant frequencies, it is possible to infer information about loading on the membrane. In fabricating FPWs, it is important to understand the impact that minor defects can have on operation. Through modeling and testing, we are developing resilient designs that provide large amplitude signals with a high tolerance to defects. A finite element model has been developed to perform design trade-off studies, and results from the model are being verified with a unique measurement system that can image Angstrom scale displacements at vibrational frequencies up to 800 kHz. Results from FPW modeling and imaging efforts are presented in this paper.

INTRODUCTION

For the past few years, Sandia National Laboratories has been developing flexural plate wave devices (FPW) for sensor applications. In this device, silicon is removed beneath a silicon nitride layer to create a small (~3 mm x 3 mm), prestressed drumhead. Serpentine transducer lines are formed on top of this membrane, as illustrated in Fig. 1, and a magnetic field is imposed by permanent magnets. Lorentz forces cause the membrane to vibrate when an alternating current passes through the transducer line. When the membrane vibrates at a resonant mode frequency, a measurable change in impedance is observed at the input port of the device. Resonant modes of the device are affected by stresses in the membrane and loads on the membrane surface. By tracking the resonant frequency of the device, it is possible to use FPW sensors to measure pressure, temperature, viscosity or density of a fluid in contact with the membrane. If absorbent coatings are applied to the surface of the membrane, it is also possible to use FPW devices in chemical detection applications.

Recent tests have highlighted obstacles that can be encountered in fabricating and using FPWs. For instance, transducer lines are not always perfectly aligned with the nitride membrane or the shape of the membrane is sometimes not perfectly rectangular. These fabrication irregularities can cause a reduction in the output signal, but tolerance to these errors is not well understood. The output signal is also a function of the vibrational amplitude and mode structure. Prestress in the membrane will affect both of these characteristics, with higher amplitudes occurring with lower membrane stresses.

Figure 1. Operation of a flexural plate wave device.

Earlier work enhanced our understanding of these devices by exploring the analytical solution for partial differential equations describing rectangular plate vibrations [Landau and Lifshits, 1986]. Using these solutions, Butler, Martin, Spates and Mitchell [1997], derived an expression for the impedance of FPWs as a function of frequency. This work was expanded using an equivalent circuit analogy to show the effects of fluid loading on the membrane [Martin,

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Butler, Spates, Mitchell, and Schubert, 1998]. While these analyses provided basic insights into the operation of FPWs, they did not provide the level of detail needed for a complete design analysis. Here we discuss a finite element model that allows us to look at specific features of an FPW design. The model is used to explore such features as the transducer line positioning and thickness, membrane tension, and membrane size. Fluid loading is ignored in this analysis. This paper also presents results from a laser-based microscopy system that has been developed to image the resonant mode structures of FPW devices. Imaging FPWs while they are driven at specific modal frequencies provides further insights into the operation of these devices.

MODELING

A finite element model (FEM) of the FPW was developed using Structural Research & Analysis Corporation's COSMOS/M FEM package with the Advanced Dynamic Module for the dynamic portion of the analysis. The analysis was conducted by first solving for the eigenmodes of a pre-stressed membrane, and then solving for the element displacements induced by an oscillating normal pressure load imposed along the transducer lines. The FPW was modeled using layered shell elements where one layer is the membrane, and the second layer is the transducer line. All six degrees of freedom were locked along the edges of the membrane in this model (see Fig. 2). A pre-stress was created in the membrane by performing a thermal analysis where the membrane cools from an unstressed elevated temperature. Tensile stresses in the silicon-nitride films have been measured to be between 80 MPa and 230 MPa [Adkins, 1999, USC Information Sciences Institute, 1999].

The effective load along the transducer lines can be calculated using Lorentz's equation for force on a conductor in a magnetic field [Hammond, 1975]. If B is the magnetic field strength, and I is the current in the conductor perpendicular to the field, then the force over a unit length, δL , is given as $F = B I \delta L$. For a conductor of width w , the effective normal pressure load on the conductor is

$$P = \frac{B I}{w} \quad (1)$$

Typically, the magnetic field strength is around 0.4 Tesla (1 Tesla = 1 N/A m), and the current through a single transducer line is around 100 μ A, so the induced load on a 100 μ m wide, transducer line is on the order of 0.4 Pa.

In the case of an oscillating current, the electromagnetic forces place an oscillating load on the membrane. To solve for the displacement of the membrane, the COSMOS/M Advanced Dynamic Module solves the equations of motion for a linear dynamic system given by the equation of motion,

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{f(t)\} \quad (2)$$

where $[M]$ is the mass matrix for the finite element system, $[C]$ is the dampening matrix, $[K]$ is the stiffness matrix, $\{u\}$ is the displacement vector and $\{f(t)\}$ is the time varying force vector [SRAC, 1997]. COSMOS/M solves Eq. 2 by the method of modal analysis; Eq. 2 is broken into a series of uncoupled second order differential equations using the eigenvectors (modal shapes) and eigenvalues (natural frequencies) of the undamped finite element system of equations. The resulting linear system of differential equations that describe the

Figure 2. FPW test device used for model studies. Ten 0.65- μ m thick aluminum transducer lines are located 160 μ m apart on a 0.62- μ m thick silicon-nitride membrane. Points A, B, and C are at the center of the transducer lines.

damped, forced vibrations of the membrane are then solved to determine the relative contribution of each fundamental mode structure (eigenvector) to the displacement matrix. The final deformed shape of the membrane is a composite of all of the mode structures up to and beyond the driving frequency of the system [see Tse, Morse, and Hinkle, 1978]. COSMOS/M offers several options to model damping in the system. For this analysis, a modal damping was selected with a damping coefficient of one percent of critical damping for each natural mode shape.

MODEL RESULTS

The modeled device was made with a 3.2-mm square silicon nitride membrane that was 0.62- μ m thick. Ten aluminum transducer lines were deposited on the membrane (see Fig. 2) to create a system with a wavelength, λ , of 640 μ m. The transducer lines are 160- μ m wide ($\approx \lambda/4$) and 0.65- μ m thick and they were spaced 160 μ m apart with an 80- μ m spacing from the edge of the membrane. All ten transducer lines can simultaneously drive the FPW, or several combinations of edge and interior transducer lines can be driven separately. Current travels in opposite directions between adjacent transducer lines, so the applied force is in opposing directions, but normal to the membrane at each line. Based on properties in the MEMS database [USC Information Sciences Institute, 1999], Young's modulus for silicon nitride is 385 GPa, Poisson's ratio is 0.27, and the density is 3100 kg/m³. For aluminum, Young's modulus is 73 GPa, Poisson's ratio is 0.3, and the density is 2768 kg/m³ [Popov, 1976]. A prestress of 150 MPa was introduced in the membrane by applying a static differential thermal contraction in the model.

In using FPW devices, we typically track the frequency where the largest shift in impedance occurs. It is generally assumed that the largest impedance shift occurs when the entire length of a transducer line moves in the same direction, and adjacent transducer lines move in opposing directions. This would be referred to as the 10x1 mode shape for the FPW shown in Fig. 2. For the modeled FPW, this behavior is observed in the 89th eigenmode which occurs at 264

Figure 3. Displacements at Points A, B, and C in Fig. 2 as a function of frequency. All 10 transducer lines are driven.

kHz. The first eigenmode which has a 1x1 mode shape occurs at about 40 kHz. The driving frequency for the 10x1 mode shape is roughly proportional to the square root of the membrane pretension [Martin et al, 1997]; halving the pretension will reduce the driving frequency by 29 percent. Similar behavior is observed with the finite element model.

The finite element model was used to determine both the structure and amplitude of the vibrating membrane. When the FPW is driven by a 660 μ A alternating current in a 0.48 T field, the transducer lines apply a 2 Pa load on the membrane according to Eq. 1. The displacement of the membrane at Points A, B, and C in Fig. 2 is shown as a function of the driving frequency in Fig. 3. A peak displacement amplitude of 118 Å occurs at the center of the transducer lines when all ten transducers are driven with a 264-kHz, 660- μ A alternating current. This peak corresponds with the 10x1 mode described above. The minor hump (~50 Å) that is observed around 274 kHz corresponds to the 10x3 mode shape and the 20 Å peak at 294 kHz occurs when the 10x5 mode is excited. In general, it is desirable to have discrete mode structures with a wide frequency spacing between adjacent modes. This characteristic makes it easier to track the impedance output of the FPW device.

When driving all ten transducer lines, there is a great deal of symmetry in displacements on the FPW surface, as might be expected. In applications with two-port devices, however, only a portion of the transducer lines is driven, and the remaining lines are used to pickup the output signal, or they are grounded to reduce noise. Symmetry is lost in this situation and maximum displacement peaks can occur at frequencies where several natural modes are combined. Figure 4 shows the displacement at Points A, B, and C (see Fig. 2) when the FPW is driven with the four left-most transducer lines. Once again, the dominant peak occurs at 264 kHz when the 10x1 mode shape is excited with the 660- μ A current. The maximum displacement, however, is about 50% higher on the undriven side of the FPW (65 Å on the undriven side compared to 37 Å on the driven side). Between 252 and 264 kHz the displacement amplitudes of the membrane remain relatively high as the membrane transforms from a 9x1 mode structure to a 10x1 mode structure. Figure 5 shows the shape of the membrane at a driving frequency between these two fundamental modes. At this frequency, the higher amplitudes actually occur on the undriven transducers, so the induced current on the right-four lines

will be significant. In a two port device, these induced currents will broaden the output signal around the fundamental mode. The output signal from a device is a product of the velocity of the transducer line and the magnetic field strength integrated over the length of the line. The calculation to determine the induced output current was not performed here, but it will be addressed in future work.

In addition to studying the effects of how the FPW is driven, several other parameters were studied with the model. The FPW pictured in Fig. 2 with all ten transducer lines driven was used as the standard for these parametric studies. The amplitude of vibration was found to be proportional to the magnitude of the driving current, as would be expected for a linear elastic FEM formulation. (It is reported, however, that stiffening occurs for larger amplitude driving currents, because large displacement amplitudes begin to induce stresses comparable to the membrane pretension [Martin, et al, 1998].) The FEM model also predicts that doubling the electrode thickness from 0.65 μ m to 1.30 μ m decreases the 10x1 mode excitation frequency from 264 kHz to 229 kHz, while the peak displacement amplitude only declines by about 5%. When the spacing between the edge of the transducer lines and the edge of the membrane increases from 80 μ m to 100 μ m, the maximum displacement amplitude increases by 3% and the frequency needed to excite the 10x1 mode decreases to 261 kHz. If the transducer lines are offset by 20- μ m from the center of the membrane, then the peak displacement amplitude increases on the side with the wider edge spacing by about 25%, and the peak decreases by about 50% on the side with the narrower edge spacing. This stands in contrast with results from perfectly centered electrodes where displacement amplitudes are nearly uniform across the membrane for the 10x1 mode. It is likely that a 20- μ m location error could significantly impact the impedance shift experienced at resonant frequencies.

Figure 4. Displacements at Points A, B, and C in Fig. 2 as a function of frequency. Only the left four transducer lines in Fig. 2 are driven.

Our standard FPWs have about 19 transducer lines on a 4-mm x 4-mm membrane. The COSMOS/M code, however, has a 150-eigenmode limit on the solution of dynamic problems, and the 19x1 mode structure occurs near this limit. For the purposes of model verification, a special series of FPWs were constructed with 10 transducer lines and the dimensions described above. The impedance of the device was measured with a Hewlett Packard 8751A network analyzer, and the results are shown in Fig. 6. A major impedance shift occurs at about 262 kHz; and minor peaks occur at 255 kHz, 276 kHz, and 305 kHz. The 262 kHz peak corresponds with predicted 10x1 mode occurring at 264 kHz in Fig. 3. The 276 kHz and 305 kHz peaks would correspond to 10x3 and 10x5 modes respectively. When driving the four left transducer lines, major impedance peaks occur at 249 kHz and 262 kHz. These correspond to the 9x1 and 10x1 modes shown in Fig. 4 that are predicted to occur at 252 kHz and 264 kHz respectively. Overall, it appears that the location of the predicted displacement amplitude peaks align well with the measured impedance peaks for the device, but we have not yet verified the mode shapes in the test device. For this purpose, we developed the imaging system discussed in the next section.

IMAGING FPW MODE STRUCTURES

One of the unique capabilities that Sandia has developed over the past few months, is the ability to image surface oscillations of FPW devices using a laser based synchronous microscopy system. This is accomplished by focusing a collimated HeNe laser beam to a 10- μ m spot on the surface of the FPW. The reflected light is projected onto a FIL-C10D silicon photodiode manufactured by UDT Sensors Inc.. A 1-radian change in the slope of the FPW surface causes about a 100-nA change in the output signal of the photodiode. A two-channel phase-lock amplifier based on the Analog Devices AD630 Balanced Modulator/Demodulator chip was built to track and measure these small-amplitude, high-frequency signals at the driving frequency of the FPW. The spot is scanned over the surface of the FPW to measure the slope at selected intervals. Scanning at 20- μ m x 20- μ m intervals requires about one hour to acquire an image of the surface. The resulting profile can be integrated along the surface to produce a topographical map showing the mode structure.

FPW devices are extremely sensitive to temperature changes; a 1°C increase in temperature can cause a 3 kHz decrease in resonant frequency. Heating from the laser and changes in ambient conditions cause the resonant frequency to drift during the imaging process. To avoid this problem, a tracking system was used to lock-in on the impedance shift associated with resonant mode structures. An impedance sweep was performed prior to imaging the device, and the system was locked on the peak of interest.

The highest impedance peak occurred at 257 kHz under the conditions of the imaging run. This corresponds to the measured 262 kHz peak shown in Fig. 6. The measured slope profile for the FPW surface is shown in Fig. 7. For this image, the driving frequency was 257 kHz and the current was estimated to be around 500 μ A. The amplitude of the slope, A_s , is approximately 30 μ rad which corresponds to a peak normal displacement of about 31 Å ($=\lambda A_s/2\pi$). The frequency is within a few percent of the predicted frequency for the 10x1 mode, and the measured amplitude of 31 Å is comparable with the predicted peak amplitude of 89 Å. The difference in amplitude could be attributed to power attenuation in lines leading to the FPW test device, or to the material properties used in the model. Higher damping in the device could be reducing the vibrational amplitude, but it is likely that the damping estimate in the model was

too high, rather than too low. By comparing the predicted peak width in Fig. 3 with the measured peak width in Fig. 6, it appears that the model damping was overestimated by about a factor of 2. Halving the modal damping coefficient in the model produces a narrower resonant frequency peak but the predicted amplitude doubles.

Figure 8 shows that the 10x3 mode is being excited when all of the transducer lines are driven at a frequency of 270 kHz. For comparison, the 10x3 mode shape was predicted to occur at 274 kHz using the FEM model. When the four left transducer lines are driven at 257 kHz, the 10x1 mode is excited, but the measured amplitude is reduced by about 60% compared to when all lines are driven. This is reasonable since the area driven by the transducer lines is also reduced by 60% when only 4 lines are powered. The second highest impedance signal was observed at 245 kHz when the FPW is driven with four transducer lines. The surface slope profile in Figure 8 shows that this frequency corresponds to a 9x1-mode shape. In the FPW model with four active transducer lines, the 9x1 mode was predicted to produce amplitude peaks nearly as large as the 10x1 mode. Imaging results verified this prediction.

DISCUSSION AND CONCLUSIONS

Sandia is in the process of developing magnetically driven flexural plate wave devices for sensor applications. The devices have applications in chemical detectors, load sensors, and gas property analysis. With recently developed finite element models, we can now explore the operation of these devices when design parameters, such as transducer line placement, membrane width, and driving currents, are changed. The model showed that placement of the transducer lines on the membrane is critical, and that providing a slightly wider clearance near the edges could slightly improve operation. With a newly developed imaging system, we are able to measure the topology of the membrane when it is driven at resonant frequencies. The imaging confirms that the model is properly predicting the mode structure. Predicted displacement amplitudes are within an order of magnitude of the measured results. Fluid loading, structural damping, and errors in the measured input power may contribute to the differences between measured and predicted results. In the future, further parametric design studies will be performed and a subroutine will be developed to integrate the predicted surface displacement and velocity results to determine the impedance shift observed in the FPW devices.

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Figure 5. Predicted mode structure at 258 kHz when the FPW in Fig. 2 is driven by the left four transducer lines. This structure occurs between the 9x1 mode and the 10x1 mode shown in Fig. 4.

Figure 7. Measured slope profile on the test FPW driven by ten transducer lines at 257 kHz to excite the 10x1 mode. Under test conditions, 257 kHz corresponded to the highest measured impedance peak of the device. The top image shows the relative location of the transducer lines.

Figure 6. Measured impedance of a ten transducer line FPW driving all lines, and 4 left lines.

Figure 8. Measured slope profile when all ten electrodes are driven at 270 kHz to excite the 10x3 mode.

Figure 9. Measured slope profile when FPW is driven by the left-four transducer lines shown in Fig. 6. Here the device was driven at 245 kHz to excite the 9x1 mode. Under the test conditions, 245 kHz corresponded to the second highest impedance peak for the device.