MEMS-Based Scanner Dedicated for Ultrasound Medical Imaging

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***Abstract*—In this paper, the development of a micro electromechanical scanner incorporating high frequency ultrasound transducer operating at 3.5 MHz is presented. We describe the structure and analysis of a microsystem that can be used as a scanner in based medical imaging system. The scanner consists of a rectangular platform attached to a frame actuated using four trapezium electrodes. The behavior of the scanner has been modeled using finite element analysis. The scan angles are up to ±5° for the platform and ±2° for the frame. Currently, the scanner is being fabricated according to the standard PolyMUMPs process. We propose this kind of scanners since it offers reduced size, power consumption, and increased speed, positioning accuracy, parallelism using arrays and reliability.**

I. Introduction

The Echography is a medical imaging technique which is used to explore surfaces human organs (thyroid, muscle, and articulation and/or deep ones (liver, pancreas, kidney, bladder, etc.). It uses an ultrasonic beam with a frequency range from 2.5 to 10 MHz, which is reflected by tissues and organs. The image quality of medical ultrasound was enhanced sufficiently to make it an indispensable modality in the diagnosis and quantification of a large number of pathologies. However, ultrasound imaging still suffers from a number of constrains that limit its potential characteristics to be fully revealed. Three dimensional ultrasound imaging is a way to get rid of most of those restrictions and to overcome the limitations. The MEMS based scanning technique provides an imaging profile that reduces the variability of the conventional technique and allows the diagnostician to view the anatomy in 3D.

Actually, there are two main scanning techniques that are used in order to plot 3D images [1]. The free-hand acquisition technique includes three basic components of acoustic, articulated arm, and electromagnetic positioners. The components make it possible to calculate the exact relative angle and position of the ultrasound probe and to ensure that no significant gaps are left. This scanning technique offers great flexibility. But, it suffers from noise and scanning gaps which may reduce the image quality, particularly when high resolution imaging of small structures is required.

The mechanical localizers' technique performs scanning using a motor which rotates the transducers. It does its task in a fan or rotational scanning method. In the latter technique, the third dimension is obtained by mechanical movement of the transducer in a precise and predefined manner. The main disadvantage of this scanning technique is the vibrating movement of the motor when it goes from one step to another. This vibration turns out in artifacts which affect the image quality.

In order to avoid these limitations, we propose to rotate a linear transducer array by using silicon scanner constructed by micro electromechanical systems (MEMS) process. This device collects 2D images while moving at predefined spatial intervals. This leads to an imaging sequence that samples the volume of interest properly, without missing any region. In order to implement the proposed scanner, each transducer is mounted on a platform, which in turn, will be actuated to rotate for sweeping over the region being examined. The use of such MEMS-based scanner in ultrasound has begun by using a table-mounted transducer which is tilted using a miniature linear actuator to produce a sector scan [2]. This actuator is an integrated force array which consists of networks of hundreds of thousands of metallized polyimide plates. These plates form micron scale deformable and flexible capacitors, which contract when an electrostatic force is produced between the plates by a differential voltage applied across them. However, this scanning technique offers only one degree of freedom actuation and its fabrication process is not a standard one. In addition, the fabrication of a matrix of hundreds of thousands plates should is required for most ultrasound applications. For those reasons, we propose a MEMS-based scanner which can be fabricated according to the standard MUMPs process and can be actuated using four electrodes. In actuating the platform, the ultrasound field in the image plane will be increased. On the other hand, actuating the frame, the collection of data from many planes can be achieved.

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Moreover, when both platform and frame are actuated additional planes or angles in the human body can be diagnosed. Therefore, platform designs and actuation mechanisms must be properly chosen such that it offers the most suitable design and dynamics for ultrasound application.

II. E DESIGN CHARACTERISTICS

The design of the proposed ultrasound scanner consists of a rectangular platform attached to a frame. Both the platform and the frame are free to rotate with respect to orthogonal axes. This device is actuated using four trapezium electrodes; two electrodes are placed under the platform and two under the frame. Fig 1. shows finite element meshes of the scanner.

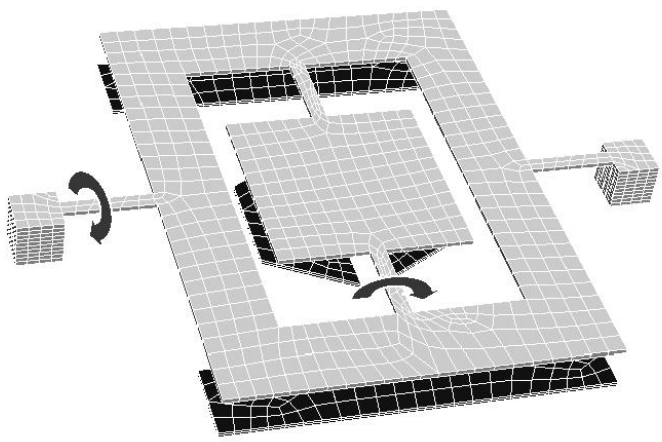


Fig 1. CoventorWare finite element mesh of the MEMS based scanner

The main reason for using trapezium electrodes is to avoid the electrostatic interference when the platform is tilted in rotating within the frame, the electrostatic force between the platform and the electrode is greater at the deflected edge near the activated frame electrode. This is due to non-linear increase in electrostatic force while decreasing the gap.

The actuation is accomplished by applying a voltage across one side of the platform and a fixed electrode underneath. The resulting electrostatic torque pulls the platform toward the electrode. This torque also rotates the platform while a restoring torque is generated by the twisting torsion springs which support the platform. The restoring torque at an angle θ is

$$\mathrm{T_m} = K_\theta \theta \tag{1a}$$

where K_θ is the spring constant. For a torsion beam with the length of l, width of w, and thickness of t, the spring constant is given as follow

$$K_\theta = 2 \times \frac{Gwt^3\theta}{3l}[1 - \frac{192}{\pi^5}\frac{t}{w}\tanh\frac{\pi w}{2t}] \tag{1b}$$

where G is the shear modulus.

On the other hand, the electrostatic torque can be calculated by integrating the electrostatic pressure over the platform surface which is common with the trapezium electrode. It can be expressed by

$$T_e = \int_0^L P.f(x)dx \tag{2a}$$

where the electrostatic pressure, P, is

$$P = \varepsilon \frac{E^2}{2} \tag{2b}$$

$$f(x) = \frac{(y_2 - y_1)}{x_1}x + y_1 + y_2 + \frac{(y_1 - y_2)}{(L - x_2)}x - \frac{x_2 y_1 - y_2 L}{L - x_2} \tag{2c}$$

the electric field, E, at x is

$$E = \frac{V}{a} = \frac{V}{(\frac{d}{\sin\theta} - x)\alpha} \tag{2d}$$

and the length of the arc on the platform, a, is

$$a = (\frac{d}{\sin\theta} - x)\alpha \tag{2e}$$

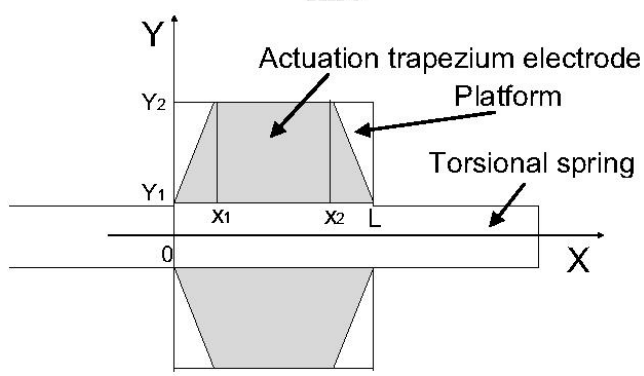


Fig.2. Schematic of platform, trapezium electrode, and beam torsion used for analytical calculation of electrostatic torque caused by an applied voltage to one platform electrode.

By equalizing equations (1a) and (2a) we can obtain the following relation between the platform angle and the applied voltage

$$V^2 = \frac{4Gwt^3\gamma}{3l\varepsilon W\lambda}\alpha^3 \tag{3a}$$

where,

$$\gamma = (1 - \frac{192}{\pi^5}\frac{t}{w}\tanh\frac{\pi w}{2t}) \tag{3b}$$

$$\lambda = (\frac{y_2 - y_1}{x_1})[\ln(1 - \frac{x_1 \sin\theta}{d}) + \frac{x_1 \sin\theta}{d - x_1 \sin\theta}] +$$
$$\frac{y_1 x_1 \sin\theta}{d - x_1 \sin\theta} + (\frac{y_1 - y_2}{x_3 - x_1})[\ln(\frac{d - L\sin\theta}{d - x_2 \sin\theta})] +$$
$$d(\frac{y_1 - y_2 - x_2 y_1 - y_2 L}{L - x_2})(\frac{1}{d - L\sin\theta} - \frac{1}{d - x_2 \sin\theta}) \quad (3c)$$

The platform is attracted toward the fixed electrode by the electrostatic torque (T_e) until it is balanced by the mechanical torque (T_m). By equating the said torques a relationship between applied voltage, V, and the platform beam rotation angle, θ, can be reached. It takes into account the dimensions of the platform (W and L,) and the arc on the platform at x, a as a design parameter.

The behavior of the frame is modeled in the same manner as the platform torsion. Following the same calculations for the frame geometry and frame rotation angle (e.g. by integrating the electrostatic pressure over the frame surface which is common with the frame electrode $T_e = \int PWxdx$, and equating this torque and the mechanical one given by equation (1), the voltage applied to one frame electrode, V, as function of the rotation angle, β, is obtained as

$$V = \frac{4Gwt^3 \gamma \beta^3}{3l\varepsilon W \lambda} \quad (4a)$$

where L and W , in this case, are respectively the length and the width of the frame, ε is the dielectric constant of the air and

$$\lambda = \{\frac{\frac{L}{2}\sin\alpha}{d - \frac{L}{2}\sin\alpha} + \ln(1 - \frac{\frac{l}{2}\sin\alpha}{d})\} - \{\frac{(\frac{L}{2} - Le)\sin\alpha}{d - (\frac{L}{2} - Le)\sin\alpha}$$
$$+ \ln(1 - \frac{(\frac{L}{2} - Le)\sin\alpha}{d})\} \quad (4b)$$

At sufficiently large angle, the electrostatic torque pulling the platform down starts overcoming the restoring torque pulling the spring up and the platform is abruptly pulled toward the fixed electrode. This important behavior, which is called Pull-in, exists at the voltage-controlled parallel-plate electrostatic actuator. Torsion beam and rigid platform are designed in a way allowing only the beam to be deformed.

III. Fabrication Process

The scanner was fabricated using the MUMPs process [4], which has the general features of a standard surface micromachining process: polysilicon layers are used as structural material and can be suspended above the wafer surface. Phosphosilicate glass (PSG) is used as oxide sacrificial layers, and silicon nitride is used as electrical isolation between the polysilicon and the substrate. Due to MUMPs process maximum gap height limitation, the gap between the platform/ frame and the electrode is limited to 2.75 microns. This is not sufficient to obtain large deflection angle. In order to raise the platform much higher over the electrodes, a flip-chip assembly technique is being used.

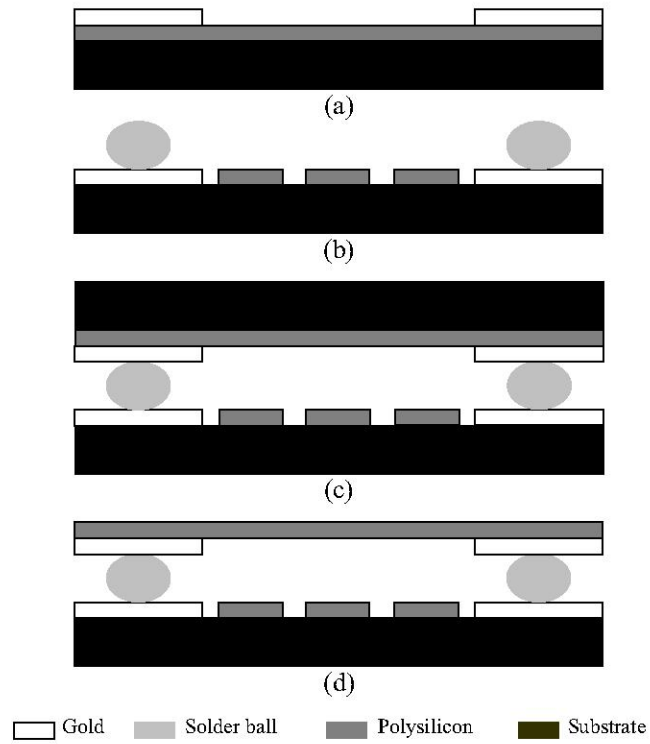
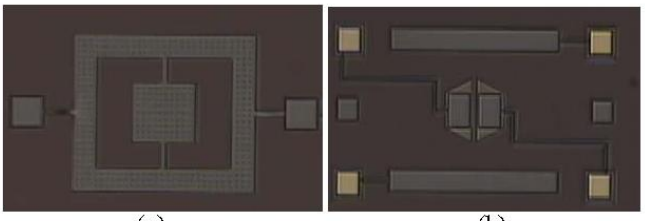


Fig 4. Illustration of the fabrication process

The platform host chip and the receiving submount chip are both prefabricated as part of the same MUMPS run where chips can be subdiced in order to have two separated chips which will be ultimately assembled. Fig. 4a shows the scanner chip which contains the platform attached to the frame layer, the torsion beams, and the upper flip-chip bonding structures. Fig. 4b shows the receiving submount chip which contains electrodes, pads and lower flip-chip bonding structures formed in the upper structural layer. The scanner is supported only by the first oxide layer and is not directly anchored to the substrate such that it will separate from the substrate when the oxide between them is etched away [5]. In addition, solder is applied to this later by ball placements on gold bonding pads. By using a reflow process the solder is melted and formed to balls. Fig.4c illustrates the bonding step in which the platform substrate is flip-chipped in "face down" orientation and joined to the electrode substrate through the solder bumps. Fig.4d shows the

resulting scanner after releasing by removing the sacrificial oxide layer. The scanner substrate is discarded and easily floats away during the release etch.

Fig.5a shows the platform, frame, torsion springs, and the anchors fabricated on one substrate. They are made from the Poly1 layer. On the other hand, the fabricated electrodes (rectangular and trapezium) made from the poly1 layer and the pads are shown in Fig.5b.

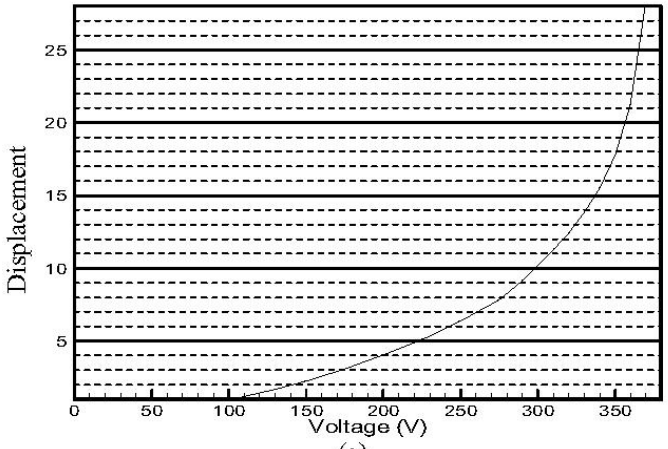


(a) (b)

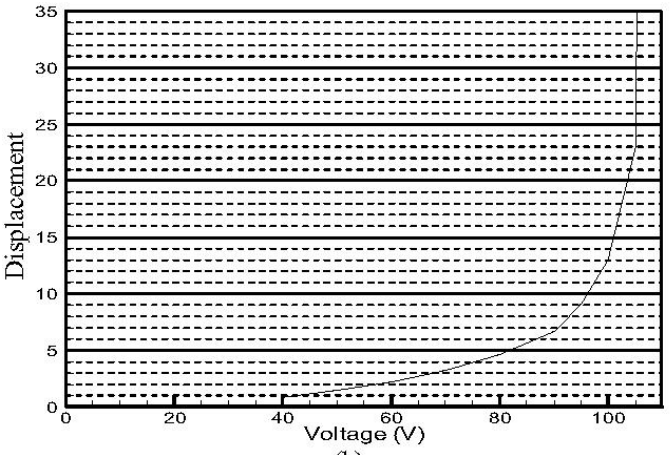
Fig 5. Photographs of the fabricated host and submount parts of the MEMS-based scanner: (a) the scanner chip (b) the electrodes chip.

IV. Simulation Results

A model of the proposed scanner and electromechanical simulation was carried out. The model includes movable platform, the torsion spring, anchors and electrodes for analyzing the scanner behavior. The volumes for movable platform and torsion spring are 260μm x 260μm x 2μm and 120μm x 20μm x 2μm respectively [3]. For boundary conditions reason, the ends of the anchors are fixed. Moreover, the voltage is applied between the fixed bottom electrode and the platform. The predicted vertical displacements of the platform at different voltages are shown in Fig. 3. It can be observed that displacement increases with the increase of the applied voltage on the electrode located underneath one platform side. The maximum platform scan angle is limited to around ±5° and the frame one is limited to around ±2°. Platform and frame pull-in detection simulations have been performed and they turned out to be respectively approximately 290 V and 92 V.



(a)



(b)

Fig 3. Numerical calculation of the scanner displacements as a function of the applied voltages: (a) platform, (b) frame electrode.

V. Conclusion

MEMS electrostatically actuated platform is a promising technology for 3D ultrasound echography. We have modeled our microsystem, which is currently being assembled, analytically and numerically using finite element software and the two models are in a good agreement. The scanner we propose will offer a continuous scanning without leaving significant gaps, an important advantage in comparison with the 3-D mechanical probe assemblies.

Acknowledgments

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