DESIGN OF DUAL ENDED TUNING FORK RESONATORS FOR ROLLER BEARING MICRO-STRAIN MEASUREMENT

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Abstract—**The strain field within automotive roller bearings is intense but small in area (~150-250 um in length.) Dual Ended Tuning Fork (DEFT) resonators fabricated in a Silicon-on-Insulator process are examined as strain sensors for this application using Euler-Bernoulli beam theory. Frequencies of between 990 ± 70and 780 ± 40 kHz were found for .25% strained DEFT's with strain sensitivities greater than 100 MHz. However, the limits of manufacturing suggest that these DEFT resonators may not be feasible for this application.**

I. INTRODUCTION:

During the standard operation of an automobile roller bearing, the small contact areas between each rolling element and the bearing race induce concentrated, high-magnitude strains. Both analytical and Finite Element Method (FEM) analyses have given insight into the magnitude and distribution of these strains [1], but the minute dimensions of the strained area (on the order of 100 microns) has made direct measurements impossible using conventional strain gauges. In addition, the high frequency of strain fluctuations and the harsh environment surrounding an operating automotive bearing further complicate the task of measuring these strains.

By virtue of their small scale, MEMS style strain gauges offer the possibility of measuring these "micro-strains" in-situ on an operating bearing. To date, various strain measurement methods have been investigated including using optical [2], piezoelectric [3], and resonant [4] methods.

Resonating sensors have been of particular interest due to their simple design and potentially high sensitivity. As a resonating beam undergoes strain it changes length**,** shifting its natural frequency. By detecting this shift, very minute strains can be monitored. Most recently, work at UC Berkeley [5]-[6], and the University of Southampton [7] has demonstrated that a dual-ended tuning fork (DETF) design fabricated in Silicon on Insulator (SOI) processes offers the frequency response, sensitivity and device-to-device repeatability required to make a practical strain sensor.

In this work we intend to investigate the frequency response of an SOI DETF. The focus will be on optimized designs for natural frequency and strain sensitivity. Dimensional uncertainty will also be analyzed.

II. DESIGN

A. Resonator Layout and Operation

The basic layout of a DEFT consists of two parallel, straight tines anchored to each other and the substrate at each end (Figure 1). For our application, external electrodes parallel to the beams electro-statically attract each tine laterally. Varying the frequency of the input sinusoidal voltage controls the frequency of excitation.

Resonance is detected by measuring the change in capacitance between each tine and electrode as they vibrate. An electrical schematic is presented in Figure 2. A high frequency signal (50 times larger than the drive frequency) is superimposed on the drive voltage. By then demodulating the output current, the change in capacitance can be detected. A simple digital accumulation of capacitance values can then mark the point of resonance.

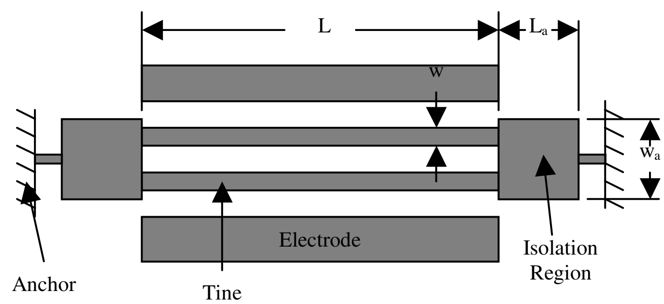

Figure 1. DEFT Layout with electrodes

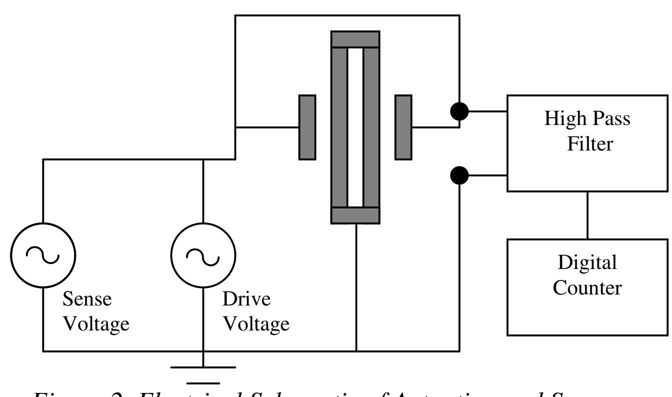

Figure 2. Electrical Schematic of Actuation and Sense Circuit.

B. Frequency Characteristics

A full description of a DEFT frequency response requires analysis of the tines, isolation region and anchors, typically through FEM analysis. However, as long as the DEFT is symmetric, and the mode of vibration is parallel to the anchoring substrate, the frequency analysis can be reduced to an examination of the resonance of the tines [8]. Further, if each tine is slender (L to w ratio greater than 10) their vibrational characteristics can be determined using Bernoulli-Euler beam theory.

Bernoulli-Euler beam theory states that a beam undergoing vibration experiences both bending and tensile forces. During its motion, cross-sections through out the beam are assumed not to rotate with respect to each other. These assumptions result in the following differential equation: [9]

$$\frac{\partial^2}{\partial x^2}\left(EI\frac{\partial^2 y}{\partial x^2}\right)+\frac{\partial}{\partial x^2}\left(F\frac{\partial y}{\partial x}\right)+\rho A\frac{\partial^2 y}{\partial t^2}=P(x)$$

Where E is the young's modulus, I is the moment of inertia of the beam, F is the axial force applied to the beam, y is the displacement of the beam in the direction of the applied force and P(x) is the shear force applied to the beam along its length.

Applying a clamped-clamped boundary condition and assuming that there is no external shear force (P(x) = 0 for all x) it can be show that the natural frequency, f_n, in Hz is: [6]

$$f_n=\frac{1}{2\pi}\sqrt{\frac{198.6EI+4.85\left(EwtL^2\right)\varepsilon}{M_{eff}L^3}}$$

where the effective mass, M_{eff}, and I are given by:

$$M_{eff}=.4\rho wtL \qquad I=\frac{tw^3}{12}$$

Simplifying, f_n can be expressed as:

$$f_n=\frac{1}{2\pi}\sqrt{\frac{16.55Ew^2+4.85\left(EL^2\right)\varepsilon}{.4\rho L^4}}$$

Differentiating this expression with respect to strain gives:

$$\frac{\partial f_n}{\partial \varepsilon_x}=\frac{3.025}{(2\pi)^2}\frac{E}{\rho L^2 f_n}$$

the strain sensitivity of the resonator. It is important to notice that both frequency and sensitivity are independent of beam thickness.

C. Actuation

Each tine will be actuated by electrostatic attraction to external electrodes. The magnitude of the force applied is given by:

$$F_{elect}=\frac{1}{2}\frac{\varepsilon AV^2}{d}$$

Where ε is the permittivity of free space, A is the area of the electrode (t * w), V is the voltage potential and d is the gap distance between the electrode and the tine.

Since the gap distance is a function of the force applied, the deflection with respect to charge is very non-linear. Limiting the deflection distance of the beam to small displacements reduces this non-linearity. This is also favorable from an energy perspective since the energy lost to the substrate is reduced with smaller deflection. Thus, in operating the resonator vibration amplitudes are limited to ~.1um. This can be achieved by limiting the gap distance to 2 um and controlling the maximum voltage applied to the electrode appropriately [7].

D. Fabrication

The resonator and electrode structures will be fabricated from single crystal silicon using a two mask SOI process with high aspect RIE etch. Mask 1 defines the resonator and electrode structure while Mask 2 defines metal contact layer. Since the frequency and sensitivity of the resonators is independent of thickness SOI depth is arbitrary; however, thicker structures increases the electrode area, reducing the voltage required for a given actuation. In addition, high aspect ratio tines are preferentially stiff in the horizontal direction, reducing the risk of out of plane or rotational modes. For these reasons, thicker SOI is preferable.

III TEST STRUCTURES

The constraints imposed by the strain field to be measured, the fabrication process involved, and the limits of digital circuitry drive the selection of test structures.

A. Design Constraints

For a typical automobile at rest, the force applied to each bearing is on the order of 2kN. Base on Hertz contact stress theory, this results in a strain field around 160 um in length. Since the strain field must be longer than the gauge length to be sensed, this limits possible L's to no greater than 160 um. This extremely small length may be overly conservative, however, since monitoring will primarily be of interest when the automobile is undergoing large dynamic load conditions. Thus, a maximum length of 230 um--corresponding to 4kN load on the bearing--was taken.

Within the strained region, the high stress is believed to produce strains on the order of a .1% or more. To be conservative the maximum strain is assumed to be .25%. Additionally, a minimum strain resolution of 1 micro-strain is desired. To insure this is possible, the minimum frequency shift for 1 micro-strain is taken to be 50 Hz (i.e. a strain sensitivity of 50 MHz).

The width and spacing of beams is limited by lithography. For state-of-the-art SOI processing 2 um width and spacing has been demonstrated in the fabrication of DEFT's [7]. Since this limit is aggressive, it is applied only where small widths are critical to the device function. Elsewhere a 4um limit is used.

Finally, in order to sense the fluctuation of the resonator, the natural frequency should be significantly higher than the ambient vibrations in an automobile (<1KHz), but sufficiently smaller than the speed of simple CMOS. In this case, a maximum CMOS speed of 100MHz was assumed, giving an upper resonator frequency of 1MHz.

B. Geometry Selection

Based on the design constraints the natural frequency for various geometries was developed. Figure 3 shows the natural frequency as a function of length and width for resonators under .25% strain. E=160 GPa and ρ=2330 Kg/m^3 were assumed. The strained state was examined since natural frequency increases with strain. Clearly, the set of acceptable beams is limited to those with large L/w ratios.

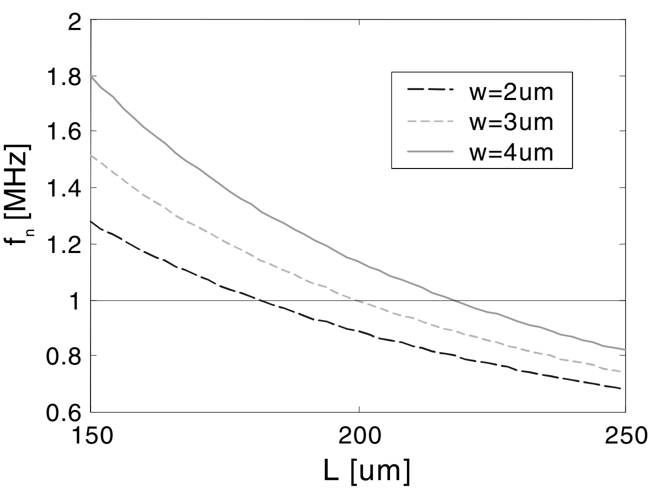

Figure 3. Natural frequency for various tine lengths and widths at 0.25% strain.

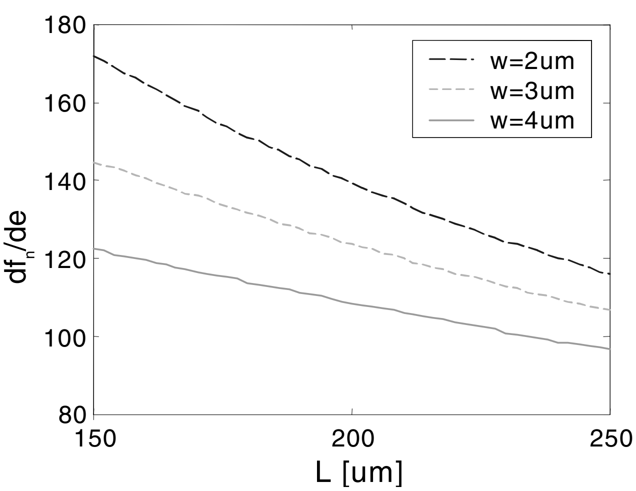

Figure 4. Sensitivity for various tine lengths and widths.

The sensitivity of various geometries is illustrated in Figure 4. As expected, all of the examined geometries have sensitivities above the desired 50 MHz mark.

The final consideration is manufacturability. For IC manufacturing the absolute variance in dimensions is independent of feature size. Larger dimensions will have a smaller percentage uncertainty. Therefore, large dimensions should be favored.

The limited range of feasible geometries limits our test structure choice significantly. Table 1 shows a tabulation of the viable geometries. In order to test the repeatability of each resonator's characteristics, five structures of each will be manufactured and tested. If possible, several thicknesses of SOI will also be tested to validate thickness independence and further repeatability.

Table 1. Resonator Geometries

Resonator	Length (um)	Width (um)
1	188	2
2	206	2
3	206	3
4	230	2
5	230	3
6	230	4

It should be noted that the design of the isolation region and anchors is not varied for each resonator. Based on previous optimization work, acceptable anchors where designed to have w_a = 16 um and L_a =14 um with 2um x 2um anchoring stubs [10]. Additionally, the gap between the beams was taken as 4um to insure proper release.

IV EXPECTED RESULTS

The behavior of the test structures is listed in Table 2. An error estimate for frequency has also calculated assuming Gaussian distribution of variance for L or ±2um and w of ± .5um.

Table 2. Expected Resonator behavior

Res	Nat. Freq. Unstrained (kHz)	Nat. Freq. .25% Strain (kHz)	Sensitivity @ .25 % Strain (MHz)
1	480 ± 120	990 ± 70	150
2	400 ± 100	880 ± 60	140
3	600 ± 100	990 ± 70	130
4	320 ± 80	780 ± 40	130
5	480 ± 80	850 ± 50	120
6	640 ± 80	950 ± 60	100

V DISCUSSION

Two interesting facts arise from an examination of the expected results. First, the frequency of all the resonators is very high. This high frequency is indirectly responsible for the high sensitivity that all the sensors exhibit, since it implies that the beams are very stiff, thus a small strain results in a large change in internal energy.

The other unexpected result is that the impact of manufacturing variation decreases with strain. There is not a simple physical explanation for this behavior. However, it may be due to the fact that under strain the beam vibrates at a higher frequency making the inertial energy more significant compared to the strain energy. The inertial energy is proportional to volume (w * L * t) whereas the strain energy is proportional to the w^3, thus the impact of the variation in w and L is lessened.

Overall, the large frequencies and high uncertainties (5%-25%) imply that these resonators may not be adequate to measure the minute strain fields in automotive applications. Especially when it is noted that the original desired length of 165um is not in the range of possible resonators, the situation looks particularly grim.

To improve this, more repeatable and greater accuracy lithography will be necessary. At a width of 1um and below, lengths on the order of 165um become possible. Still the dimensional variance would have to be less than 10% to avoid unacceptable uncertainties. Alternately, a higher top frequency will be necessary.

It should also be noted that several assumptions have been made. First, there are potentially more accurate methods of finding the natural frequency and sensitivity including Timoshenko beam theory and FEM. However, the slender aspect of these beams and previous work on DETF's suggest that these results will match these other methods to within 10% [5,7].

Also, the assumptions of no residual stress in the substrate and a Young's modulus of 160 GPa may not be completely accurate. Here, once again, the fact that these beams are to be fabricated in single crystal silicon may make these assumptions more valid. Still, care will need to be taken to insure that these material properties are verified in the manufactured resonators.

VI CONCLUSIONS

Micromachined resonators show much promise as sensing elements within MEMS devices; however, they may not always be feasible. Using a DEFT to measure the minute strain fields within automotive bearings appears to be such a case. The current limitations of micromachining make the fabrication of a gauge that can be used under normal load situations difficult. However, for high load applications--where the strain field is 1 or 2 times larger in magnitude--SOI DEFT may still offer the sensitvity and frequency needed.

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