Simulation study for reduction in natural frequency and stiffness of meander structure with constant device dimension

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ABSTRACT

Most of the MEMS structures use proof mass to reduce the frequency but increases the device dimension. This paper deals with the variation of natural frequency and stiffness of the structure when changed from rectangular to multi-turn meander structure. The suspended meander structures are designed with silicon nitride and simulation were carried using COMSOL Multiphysics FEM model to investigate the natural frequency and deflection of the structure by varying the number of turns 'N'. The simulation and Analytical results show an impact with variation of N on the natural frequency of the structure when the distance between the fixed-fixed beam is kept constant. Further investigation is carried out on the stiffness variation of multi-turn meander structure with fixed at one end.

1. Introduction

MEMS structure has always been a promising technology in all the domains such as RF Switches, accelerometer, RF resonator. Multiple challenges lie in designing the devices with specified dimension to fit on a certain die size (in order to reach miniaturization). To validate the designed structure, simulations are carried out with basic concept of solid mechanics such as natural frequency and stiffness. Stress of the material also play an important role while validation.

Meander structure are used to avoid the space or area constraints [1], in some cases they are added in order to obtain lowest possible spring constant, pull in voltage and insertion loss with high isolation loss and switching speed for MEMS switches [2,3,4], Analytical methods have also been proposed for calculation of spring constant in MEMS Switch [5] and also certain applications are intended for low-frequency and high-sensitivity, in such cases the suspended structure are designed in literature with a resonance frequency which lie in the range of targeted external input force [6].

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In this paper the comparison with impact of stress on the rectangular beam and meander structure are simulated. Further simulation are investigated for stiffness and natural frequency of the rectangular beam and meander structure by keeping the distance between two anchor pad fixed. Also, the variation in stiffness in X, Y, Z direction and natural frequency is studied with variation in the number of turns of meander structure.

2. Theory

2.1 Numerical procedure

In this research, to obtain the numerical result, the modal analysis is done in finite element software COMSOL Multiphysics. The numerical calculation of natural frequency and the mode shape is done in three main steps. Those steps are as follows [7]:

1. The geometric modelling is done
2. Required boundary conditions are applied, and modal analysis is carried out to estimate the eigen frequencies and eigen vectors
3. The theory of elastic dynamics is used to determine mode shape and natural frequencies of the system.

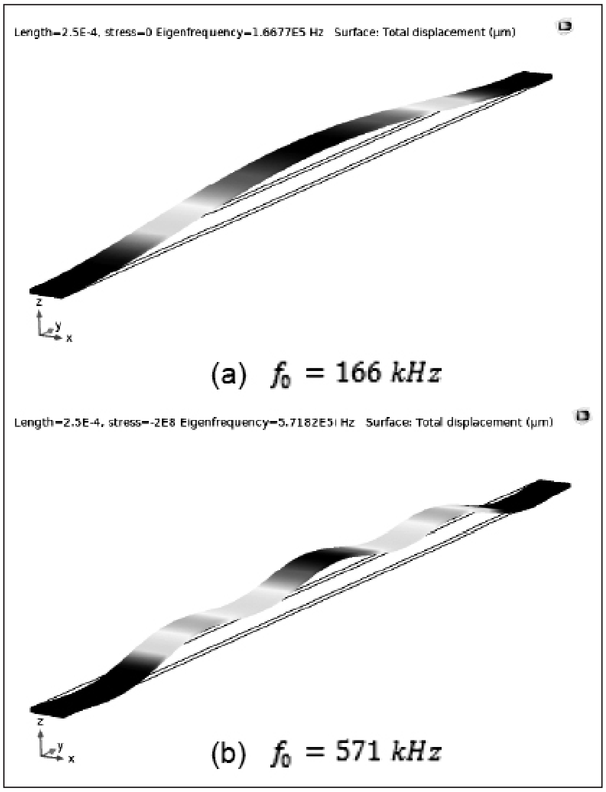

Fig. 1. Frequency of the first mode of vibration for fixed-fixed beam (a) with zero stress and (b) with 200 MPa residual stress.

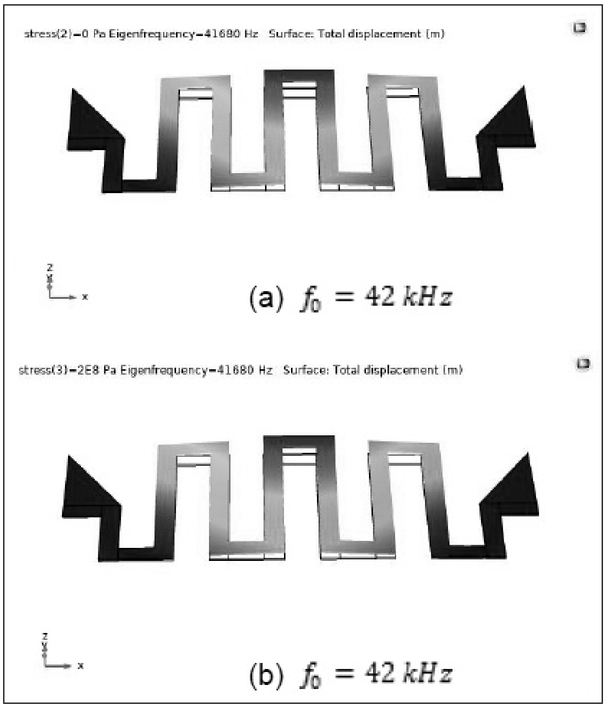

Fig. 2. Frequency of first mode for meander structure (a) with zero stress and (b) with 200 MPa residual stress.

As it is known that the general governing equation of motion for free vibration can be written as:

$$[M]\,\ddot{x} + [K]x = 0 \quad (1)$$

Where [M] is the structural mass matrix, and [K] is the stiffness matrix. If the displacement x (u, v, w) is written in terms of n eigenvectors $Ø_i$ (u,v) and the time-dependent modal coordinate $q_i(t)$ [7] as

$$x(u,v,t) = \sum_{i=1}^{n} \phi_i(u,v) q_i(t) \quad (2)$$

then the eigenvalues and the corresponding eigenvectors can be calculated from the equilibrium equations:

$$[K]\,\{Ø_i\} = \omega^2_i [M]\,\{Ø_i\} \quad (3)$$

Based on the orthogonal properties of the eigenvectors, the expressions for resonant frequencies and corresponding mode shapes can be obtained:

$$\{Ø_i\}^T [K]\,\{Ø_i\} = \omega^2_i \{Ø_i\}^T [M]\,\{Ø_i\} \quad (4)$$

$$\omega_i^2 = \frac{\{\phi_i\}^T [K] \{\phi_i\}}{\{\phi_i\}^T [M] \{\phi_i\}} = \frac{k_i}{m_i} \quad (5)$$

Where m_i and k_i are mass and the stiffness of i^{th} mode corresponding to eigenvector $Ø_i$ and the resonance frequency ω_i.

3. Results and Discussion

This research deals with the variation in the natural frequency of the system when the geometry of the structure is changed. The simulation is done for a fixed-fixed beam and the meander structure with the same device length of 250µm between fixed-fixed structure. As shown in fig.1, for a fixed-fixed beam with the length 250µm and width of 10µm, the natural frequency comes around 150 kHz when simulated without considering the internal residual stresses. However, when the simulation is done by considering the internal residual stresses measured by using KSA MOS Ultrascan machine for wafer bow and stress measurement, for the stress of 200 MPa the natural frequency increased by 3.5 times. The change in the natural frequency of the structure is shown in the fig.1.

The meander structure is made with for the same effective length of 250µm and with width of 10µm is simulated in COMSOL Multiphysics. The simulations below show that the natural

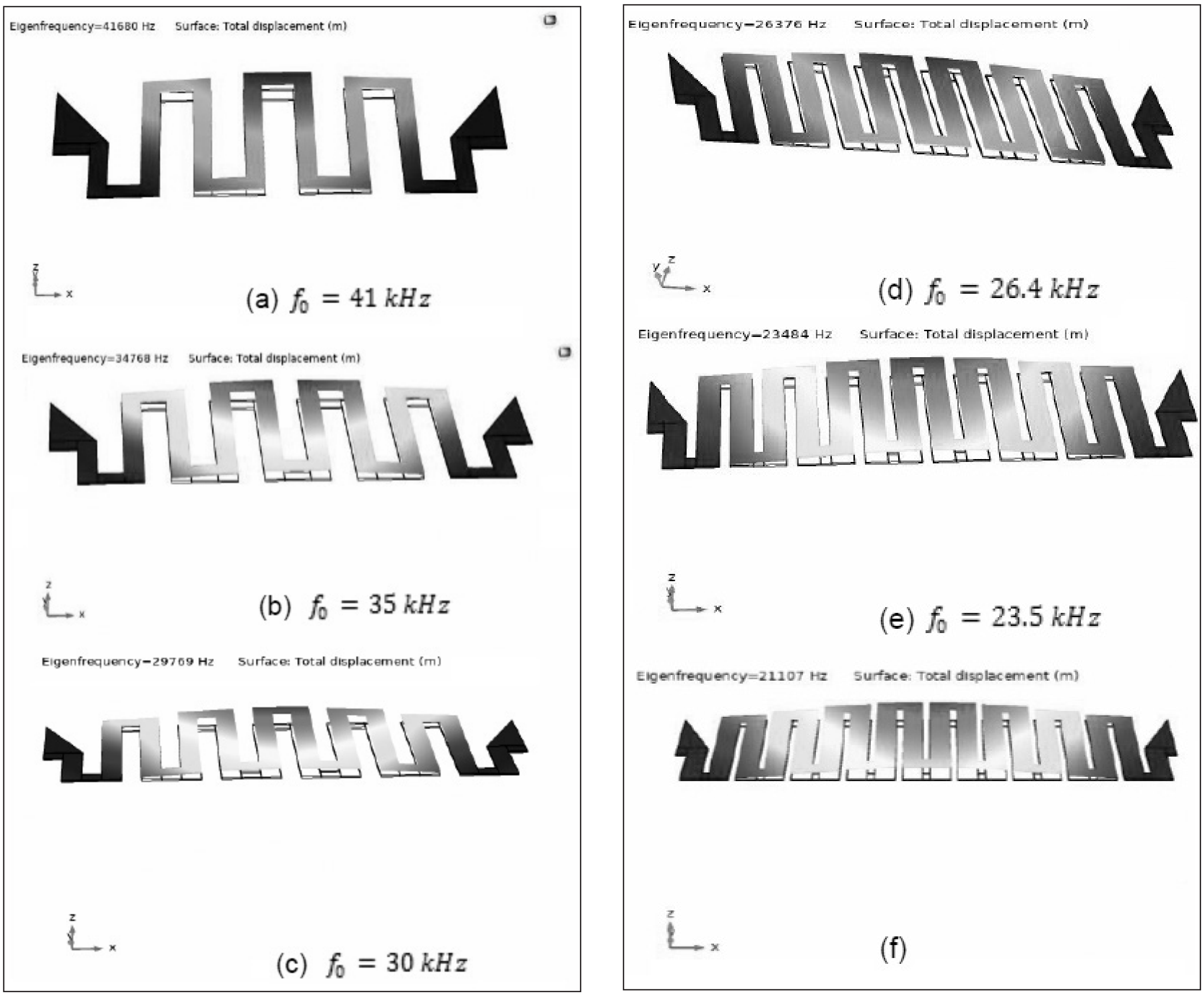

Fig. 3. (a) to (f) shows COMSOL simulated data of variation in natural frequency with increasing number of turns.

frequency for meander structure remains constant and independent of internal residual stress. Thus, by changing the geometry of fixed-fixed beam to meander structure not only the natural frequency reduces but also there is no impact of stress variation.

The further studies are done on how the natural frequency changes with respect to the variation in the number of turns in the meander structure. The figures below show the simulated result with varying the number of turns from the COMSOL Multiphysics 5.4.

To study the variation in the stiffness and the natural frequency with the changing number of turns allows optimization of structure which help in development of MEMS device [5]. This variation is stiffness and natural frequency is show in fig. 4 and 5 respectively. The fig 4 shows the stiffness of the system reduces when the number of turns is increased by keep the width

Table 1
Natural frequency of meander structure with increasing number of turns spacing.

Corresponding Fig. 3	Number of turns	Natural Frequency (kHz)
a	3	41.682
b	4	34.658
c	5	30.0031
d	6	26.376
e	7	23.487
f	8	21.105

of the beam constant to and changing the pitch between two turns which is shown by some researchers for similar structures [5,8]. As the stiffness reduces this in turn reduce the frequency of the system which is shown in fig 5. Comparing the result in fig.1 and fig. 3, it can be proved that the frequency of first mode of vibration

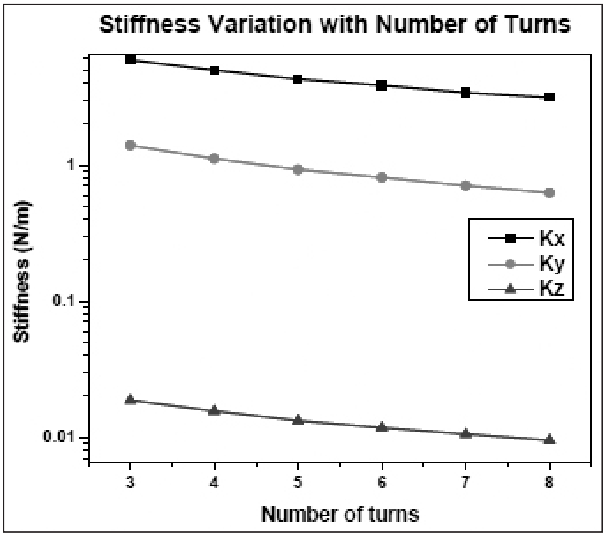

Fig. 4. Variation of stiffness with number of turns.

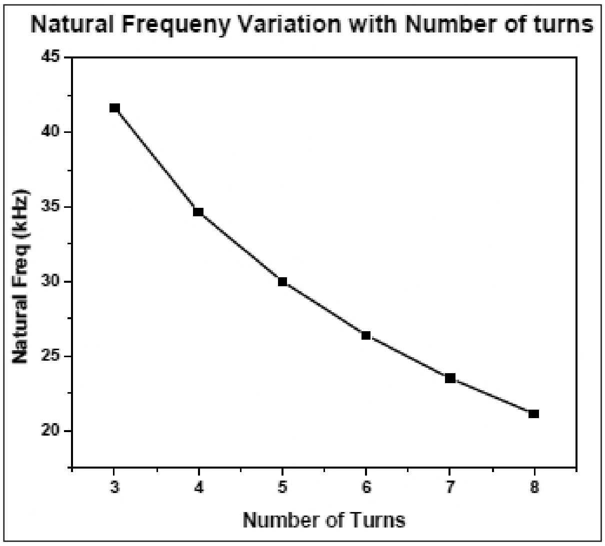

Fig. 5. Variation in natural frequency with number of turns.

drastically reduced when the meander structure is used for same compact space.

The data shows that overall length of the beam changes as the number of turns increased from zero for fixed-fixed structure to eight for meander structure. This increase in length of the structure increase the mass of the structure from fixed-fixed to meander structure while the stiffness of these structures reduce. As suggested by equation (5) the reduction in stiffness and increase in mass of the systems result in the reduction of the natural frequency of first mode of vibration of the system.

4. Conclusion

The simulation results show that the stiffness of the structure reduces in Z direction which in turn reduce the natural frequency of first mode of vibration of the meander structure reduces for same area of fixed-fixed beam. Also the simulated data show the internal residual stresses have very small effect on the natural frequency of the meander structure as compared to fixed-fixed rectangular beam with zero turn. This property of the structure can be taken advantage to design the structure with low frequency and no impact of internal stress on frequency. The simulated results presented in this paper provide the guidelines for the experimental work for different application such as MEMS Switch, Accelerometer and resonators.

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6. References

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