Analysis and Simulation of Serpentine Suspensions for MEMS Applications

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***Abstract*—In many MEMS devices, the mechanical suspension method usually creates a problem of how it should be suspended versus the design area and structure complexity. Simple designs may be able to keep complexity level down, however they do not usually hit the targeted specifications. Serpentine suspension proves to be very useful in such cases. In this paper, three serpentine suspensions are discussed and analyzed. Mathematical expressions of each serpentine are derived in terms of stiffness. The derived expressions validity was tested with COMSOL simulation, and results show very good agreement between analytical expression and simulation.**

***Index Terms*—serpentine, suspension, MEMS, stiffness.**

I. Introduction

It can be said that the field of micro-electro-mechanical systems (MEMS) was originated by Richard P. Feynman in 1959, when he made the observation: There is plenty of room at the bottom [1]. He was the first one to induce the idea of miniaturization of systems. MEMS can also be defined, as is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro fabrication technology. While the functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, the most notable (and perhaps most interesting) elements are the microsensors and micro-actuators. Microsensors and microactuators are appropriately categorized as transducers, which are defined as devices that convert energy from one form to another [2].

MEMS promises to revolutionize nearly every product category by bringing together silicon-based microelectronics with micromachining technology making possible the realization of complete systems-on-a-chip [3]. There are different types of actuators such as electro- static actuator in which the electrostatic force is created by applying the voltage across the two plates. But in order to have a large deflection or force, the suspensions that are used to carry on the movable plates need to be carefully designed.

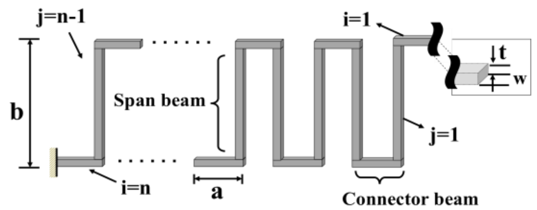
Serpentines flexures are very useful when low stiffness is required with a limited design space. By adding extra elements (meanders) to the serpentine, the overall stiffness can significantly reduced.

In this paper, the stiffness expressions for three different serpentine arrangements are discussed. Analytical expressions are then validated with simulation, and the results show good agreement between analytical expressions and simulation.

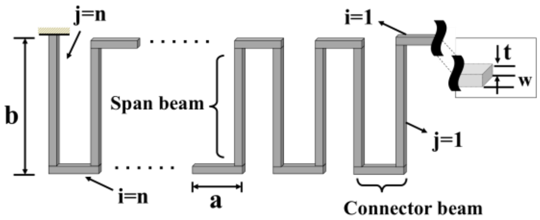
In Sections II the serpentine suspension is introduced, while in Section III both analytical derivations and simulation are presented. The results and discussions are presented in section IV, and conclusions in section V.

II. Serpentine Definition and Analysis

The serpentine suspension can be defined by repeated meanders. A single meander consists of two connector beams and two span beams. For the rest of this paper, the width and thickness of each of the connector beams and span beams are kept fixed along each serpentine arrangement.



(a)



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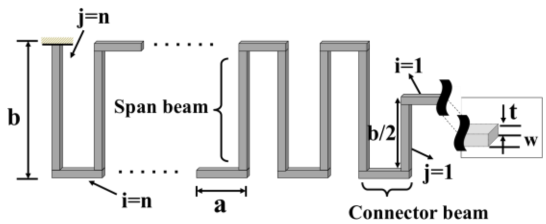

(c)

Figure 1. Serpentine arrangements.

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A. Serpentine 1

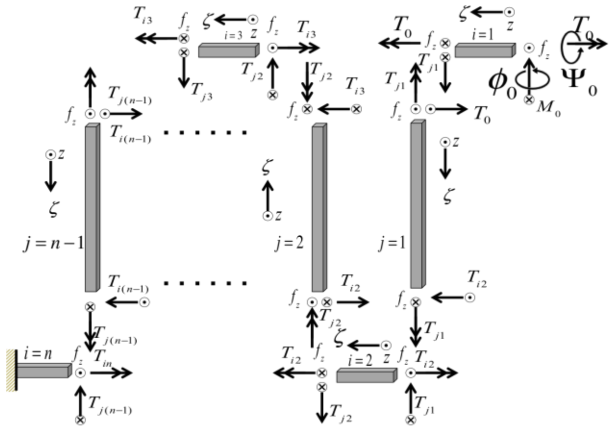

Figure 2. Serpentine 1 free-body diagram.

The first serpentine arrangement is shown in Fig. 1(a). The free-guided connector beam is connected with a span beam of the same length as the rest of the span beams. The connector beam is repeated n of times while the span beams are (n-1) times. As mentioned before, the serpentine is referred to by: the number of meanders or either the number of connector beams. The connector beam is of length (*a*) while the span beams are of length (*b*). The width of the span beams is (w_a), while the width of connector beam is (w_b). The thickness is assumed to be the same for both connector and span beams (t). The free-body diagram for calculation of the z-direction spring constant is given in Fig. 2. Force, moment and torque are examined at each beam segment using Energy method [4]-[5]. The resulting moment and torsion expressions for the connector beams are as follows,

$$M_{a,j} = M_0 - f_z(\delta + (i-1)a) \tag{1}$$

$$T_a, j = T_0 - \left(\frac{1+(-1)^i}{2}\right) f_z b \tag{2}$$

where, $M_{a,i}$ and $T_{a,i}$ are the moment and torsion of the i^{th} connector beam respectively. The bending moment and torsion for the span beams are,

$$M_{b,j} = T_0 + f_z\delta \tag{3}$$

$$T_{b,j} = M_0 - jf_z a \tag{4}$$

where, $M_{b,j}$ and $T_{b,j}$ are the moment and torsion of the j^{th} span beam respectively.

The total strain energy can be expressed by,

$$U = \sum_{i=1}^{n} \int_0^a \left(\frac{M^2_{a,i}}{2EI_{x,a}} + \frac{T^2_{a,i}}{2GJ_a}\right) d\zeta + \sum_{j=1}^{j=\mathbf{n-1}} \int_0^b \left(\frac{M^2_{b,i}}{2EI_{x,b}} + \frac{T^2_{b,i}}{2GJ_b}\right) d\zeta \tag{5}$$

Assuming a free-guided end with a rotational angles equal to zero, thus,

$$\phi_0 = \frac{\partial U}{\partial M_0} = 0 \tag{6}$$

$$\varphi_0 = \frac{\partial U}{\partial T_0} = 0 \tag{7}$$

The stiffness can be deduced from the deflection in the z-direction,

$$\delta_z = \frac{\partial U}{\partial f_z} \tag{8}$$

A MATLAB routine is used to deduce stiffness expressions for various meander numbers.

B. Serpentine 2

Another case of serpentine having equal number of span beams and connector beams–Fig. 1(b)-is analyzed in the following subsection. The free-body diagram is shown in Fig. 3. This serpentine arrangement is used for the proposed designs as it employees the best use of design area and allow the lowest stiffness possible in that area. Applying the Energy method analysis, the bending moment and torsion for connector beams are the same as Eq. (1) and Eq. (2), respectively. Similarly, the bending moment and torsion for span beams are the same as Eq. (3) and Eq. (4), however, the strain energy should include the extra span beam added in Serpentine 2, as follows,

$$U = \sum_{i=1}^{n} \int_0^a \left(\frac{M^2_{a,i}}{2EI_{x,a}} + \frac{T^2_{a,i}}{2GJ_a}\right) d\zeta + \sum_{j=1}^{j=\mathbf{n}} \int_0^b \left(\frac{M^2_{b,i}}{2EI_{x,b}} + \frac{T^2_{b,i}}{2GJ_b}\right) d\zeta \tag{9}$$

The total Serpentine 2 stiffness for various number of connector beams is derived.

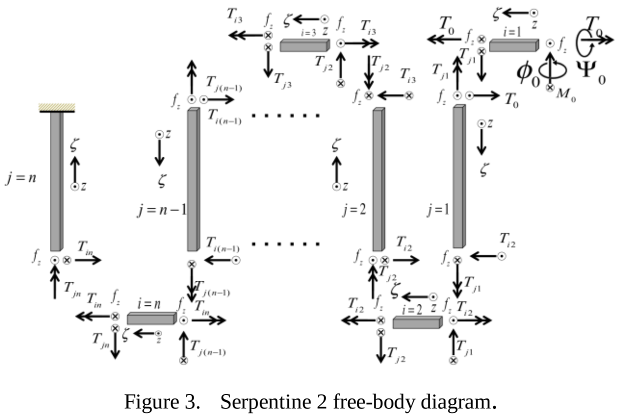

Figure 3. Serpentine 2 free-body diagram.

C. Serpentine 3

A third serpentine arrangement is analyzed that has similar geometry to Serpentine 2 but with half-ended beam as shown in Fig. 1(c), while Fig. 4 shows the free body diagram.

The bending moment and torsion for the connector beams are,

$$M_{a,i=1} = M_0 - f_z\zeta \tag{10}$$

$$M_{a,i\neq 1} = M_0 - f_z(\zeta + (i-1)a) \tag{11}$$

$$T_{a,i=1} = T_0 \quad (12)$$

$$T_{a,i\neq1} = T_0 + f_z b \quad (13)$$

The bending moment and torsion for the span beams are the same as Eq.(3) and Eq.(4), respectively while the total strain energy is calculated from Eq.(9). The total Serpentine 3 stiffness for various number of connector beams is derived.

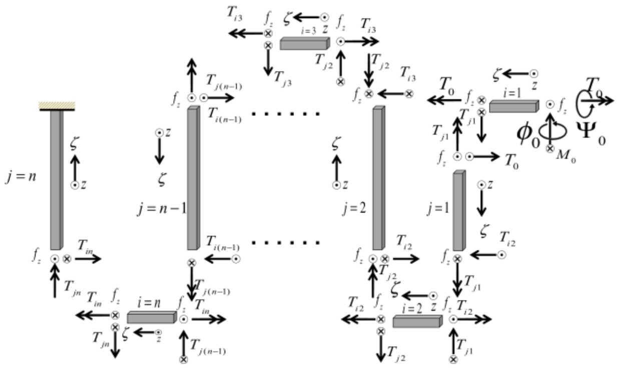

Figure 4. Serpentine 3 free-body diagram.

III. Simulation Analysis

Analysis is carried out and investigation is prepared by generating full 3D models along with simulation using Solid Mechanics module of COMSOL Multiphysics software package. The three different serpentines where built in 3D builder and corresponding boundary conditions were applied. A fixed boundary is applied on the free-guided end of the three different serpentine arrangements. The stiffness of the serpentine is calculated from the simulated deflection of the serpentine free-guided end. Fig. 5 shows an example of Serpentine 2 with three meanders in 3D builder.

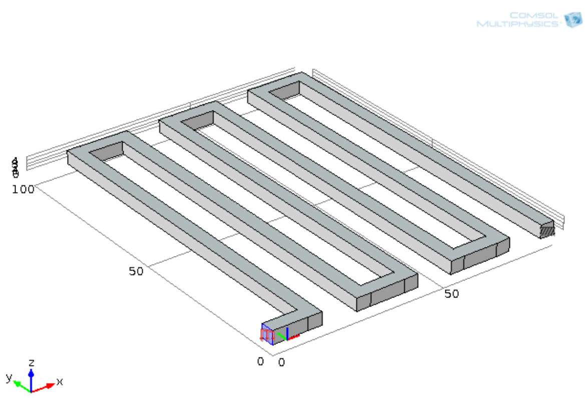

Figure 5. Serpentine 2 in COMSOL.

IV. Discussion

For Serpentine 1 and Serpentine 2, analytical expression deduced are compared with expressions from [5] and [6] and results showed very good agreement. Validation of Serpentine 2 and Serpentine 3 stiffness expressions is done using Finite Element Method FEM to compare between analytical and simulated results. Three different arrangements for serpentines were considered, as shown in Table I.

TABLE I. Serpentine Arrangments

	a	b	N
Case 1	10 µm	100 µm	6 µm
Case 2	15 µm	300 µm	10 µm
Case 3	30 µm	300 µm	8 µm

where *a* is the connector beam, *b* span beam and N is the number of connector beams. It should be noticed that the material used for all of the examined serpentines is SiGe with a Young's modulus of E = 120GPa.

To the authors' knowledge, Serpentine 3 has no literature expression to referee to it. A cross comparison between Serpentine 2 and Serpentine 3 was used and Serpentine2 was chosen to be the benchmark reference. The results for the three cases are presented in Table II and Table III. The deviation between the simulated and analytical results, for both cases Serpentine 2 and Serpentine 3 are in good agreement. This indicates that Serpentine 3 expression used was as good as Serpentine 2 expression.

TABLE II. Simulation of Serpentine 2 and Serpentine 3

	Serpentine 2	Serpentine 3	Δ
Case 1	2.186 N/m	2.396 N/m	9%
Case 2	0.073 N/m	0.077 N/m	5%
Case 3	0.052 N/m	0.056 N/m	8%

TABLE III. Analysis of Serpentine 2 and Serpentine 3

	Serpentine 2	Serpentine 3	Δ
Case 1	2.806 N/m	3.052 N/m	9%
Case 2	0.084 N/m	0.088 N/m	5%
Case 3	0.053 N/m	0.057 N/m	8%

V. Conclusion

Three different serpentine arrangements were examined and analytical stiffness expressions were deduced for each arrangement. The deduced expressions were validated with simulated results using COMSOL showing very good agreement between them. Further study of various numbers of meanders in each of the three serpentines should define the regions of accuracy of the deduced expressions.

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