Design and modeling for comb drive actuator with enlarged static displacement
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Abstract

New comb drives using high stiffness ratio springs are designed and modeled to provide capabilities of large static displacement and continuous motion for applications, such as micro XY stage, two dimensional lens scanner, variable optical attenuator, and optical switch, etc. The maximum static displacement of conventional comb drive is constrained by the side sticking effect of comb finger electrodes. Since the side sticking effect will become obvious and exhibit strong impact on actuator behavior in the case that the spring lateral stiffness is decreased when the static displacement is increased, and the rotation moment caused by unbalanced force between electrode fingers resulted from the environment disturbance and/or fabrication deviation will enhance the side pulling phenomena. The aforementioned sticking effect occurs at the static displacement smaller than the analytical results estimated by conventional stability criteria. Thus, a new stability criterion is proposed for providing more accurate predicted maximum static displacement. A new hybrid spring with an n-shaped joint for comb drive is developed and proposed in this paper as well. This new spring is capable of not only enhancing the lateral stiffness against to the lateral mechanical disturbance and shock, but also efficiently eliminating the rotation moment caused by the disturbance over the large displacement range. The design scheme is verified by the simulation results.

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1. Introduction

Developing a comb drive actuator with large static displacement and continuous motion capability is a major research interest. Actuators of such capability are crucial for practical applications such as micro XY stage, two dimensional lens scanners, and variable optical attenuators, optical switches, etc. The maximum static displacement of comb actuator is commonly limited by the side pulling effect of comb fingers in the conventional design of comb actuators [1–3]. The tiny deviations of comb finger and gap width will lead to an unbalanced force between both sides of comb electrode, and such a deviation is easily caused by microfabrication process [4]. The unbalanced force between both sides of comb finger is the major contribution factor to the side instability effect. How to design and make a comb drive actuator that is more robust to the process induced deviation is very attractive to industrial practical application purpose.

We have presented a comb actuator with thinned folded-beam spring derived by using a modified silicon-on-insulator deep reactive ion etching (SOI-DRIE) process [5,6]. This comb actuator could provide larger static displacement than traditional comb actuators. Grade et al. [7,8] reported a $1 \times N$ optical switch using multiple linear comb drive actuators, where this comb drive actuator consisted suspended pre-bent springs, as shown in Fig. 1(a). Zhou et al. [9] have modified this design into a tilted folded-beam type spring which comprises four springs tilted and located either on one side of comb electrodes, or on both sides of comb electrodes, as shown in Fig. 1(b). Both works consider the side instability effect regarding to the translational (moving directional) disturbance or process induced layout misalignment, and point out the pre-bent or tilted springs can exhibit larger lateral stiffness than the conventional springs over a certain range of static displacement. In our previous report [10], we proposed new comb drive actuator designs using four folded-beam springs located symmetrically on both sides of comb electrodes, in which one pair or two...
pairs of springs were tilted springs. The lateral (side) stiffness for these kinds of springs was analyzed by using finite element method (FEM). In this paper, we further present comprehensive analytical model to analyze the environment disturbance and process deviation induced side instability phenomena. The analytical results are verified by FEM results for these comb drive actuators. A novel comb drive springs comprising a pair of tilted springs and a pair of normal springs with an \( n \)-shaped joint is proposed. This new design is studied based on analytical and FEM models. It is very promising for applications that the large static displacement and force output are essential to practical uses. Finally a design methodology for comb drive with enlarged static displacement is discussed and concluded.

2. Analytical model and background assumptions for simulation

As shown in Fig. 2, when an electrical voltage difference is applied to the rotor, i.e. the movable comb fingers, and the stator, i.e. the stationary comb fingers, the rotor will travel toward the stator due to the electrostatic force in \( x \)-direction. The force balance between the spring restoring force and the electrostatic force determines the position of rotor. For in-plane motion applications, the side instability of moving comb will lead to limited travel distance of rotor. Because the moving comb fingers will snap and touch the fingers of stationary comb when the net electrostatic force between fingers is larger than the restoring spring force in \( y \)-direction, i.e. the side pulling phenomena, or the side sticking effect. Thus the actual maximum travelling distance of rotor will be either determined by force balance in \( x \)-direction or by the side pulling effect. Referring to [1–3], the electrostatic force along the moving direction (\( x \)-direction) in Fig. 2 is defined as

\[
F_x = \frac{N\varepsilon t V^2}{8}
\]

where \( N \) is the number of comb electrode fingers; \( \varepsilon \) the permittivity constant of air; \( t \) the comb electrode thickness; \( g \) the comb electrode gap; \( V \) the driving voltage. If the spring constant in \( x \)-direction and the travelling distance of the rotor (the movable comb electrode) in Fig. 2 are defined as \( k_x \) and \( \delta_x \), then the travelling distance (the static actuation displacement) can be derived from Eq. (1) as

\[
\delta_x = \frac{N\varepsilon t V^2}{k_x}
\]

The maximum travelling distance is constrained by the electrostatic force at both side of the electrode finger of rotor is unequal. Accordingly, the spring stiffness can not sustain the electrode fingers at a steady position between two stator fingers, the friction between them will stop the rotor travelling further more. To clarify the travelling constraints of our new comb drive actuator design, the balance
Fig. 3. (a) Simplified model of electrostatic force in \( y \)-direction when the electrode of rotor is disturbed to move away from \( y \)-axis; (b) equivalent model between the electrostatic force and spring stiffness, or the stability, is depicted in the following analysis.

When the rotor situates away from the central axis between two stator’s fingers, the position deviation can be described by a shift distance \( \delta y \) and a torsion angle \( \theta \), as shown in Fig. 3(a). Thus, the lateral electrostatic force, i.e. \( F_{ey} \), with a constant dc driving voltage can be given by

\[
F_{ey} = \frac{1}{2} \varepsilon_0 N t V^2 \int_{l_{overlap}}^{l_{overlap}} \left( \frac{1}{(g - (l_0 + \theta)|\sin \theta - \Delta|^2) - \frac{1}{(g + (l_0 + \theta)|\sin \theta + \Delta|^2)} \right) d\theta
\]

where \( l_{overlap} \) is the overlap length between electrode fingers of rotor and stator; and \( l_0 \) is the finger length without including overlap region. Assume \( \theta \ll 1 \) in Eq. (3), \( \sin \theta \) is approximate \( \theta \) and \( (l_{overlap} \sin \theta/2)^2 \) is assumed to be much smaller than \( g - (l_0 + \theta + \Delta + l_{overlap} \sin \theta/2) \) and \( g + (l_0 + \theta + \Delta + l_{overlap} \sin \theta/2) \) as well. Thus, Eq. (3.1) can be simplified as

\[
F_{ey} = \frac{1}{2} \varepsilon_0 N t V^2 l_{overlap} \left( \frac{1}{(g - (l_0 + \theta)\sin \theta - \Delta)^2} - \frac{1}{(g + (l_0 + \theta)\sin \theta + \Delta)^2} \right)
\]

\[
\delta y = l_0 \theta + \Delta + \frac{\theta l_{overlap}}{2}
\]

where \( \delta y \) is the deviated distance of the central point of overlap in \( y \)-direction from \( A \) to \( A' \), as shown in Fig. 3(b). According to Eq. (3.2), the \( F_{sy} \) effecting on the rotor’s finger in Fig. 3(a) approximately equals to the \( F_{ey} \) in Fig. 3(b), where the rotor’s finger shift from the central axis by \( \delta y \). That is, considering of the approximate \( F_{ey} \), the rotor deviation model in Fig. 3(a) can be simplified as a rotor shifting from central axis in parallel, shown in Fig. 3(b). Therefore, if the equivalent spring restoring force, i.e. \( F_{sy} \), at the central point of overlap (\( A' \)) can compete with the electrostatic force \( F_{ey} \), then the comb drive is stable; otherwise, the electrodes of rotor and stator will snap to each other due to the attraction of electrode static force \( F_{ey} \). In order to evaluate the stability of comb drive actuator, the said \( F_{sy} \) is given by the following depiction. Fig. 4(a) demonstrate the force equilibrium status when the rotor’s finger deviates from central axis with an opposite force \(-F_{sy}\). Thus the moment and force equilibrium equations are

\[
F_{sy} \left( \frac{l_{overlap}}{2} + l_0 \right) = k \delta \theta
\]

\[
F_{sy} \cos \theta = k \Delta
\]
where $k_y$ and $k_\theta$ are the spring constants along with the $y$-direction and with respect to torsion angle $\theta$, respectively. Thus, the equivalent spring constant $k_{sy}$ at the center point of overlap ($A'$) can be derived by

$$
F_{sy} \cos \theta \frac{\delta y}{k_{sy}} = \Delta + \left( \frac{l_{overlap}}{2} + l_0 \right) \theta
$$

In the case of $\theta \ll 1^\circ$, $F_{sy} \cos \theta$ is approximate $F_{sy}$. Thus, Eq. (7) can be rewritten as

$$
k_{sy} = \frac{1}{k_y} \left( \frac{l_{overlap}/2 + l_0}{k_\theta} \right)^2
$$

Referring to [1–3], the analytical $k_y$ of the folded-beams spring is given as [3]

$$
k_y = \frac{200EI}{6l_{overlap}^2}
$$

where $l$ is the second moment of inertia of beam. That is, the spring restoring force at point $A'$ in Fig. 4(b) can be considered as the equivalent spring restoring force of spring constant $k_{sy}$ extending vertically from A to A'. In conclusion, if $F_{sy}$ is larger than $F_{ey}$ when the rotor deviates from the central axis, the rotor will return to the central axis without snapping to the stator and the comb drive is stable. Referring to [1–3], the stability is further defined by the equivalent stiffness as

$$
k_{sy} = \left. \frac{\partial F_{sy}}{\partial y} \right|_{y=0} \geq \left. \frac{\partial F_{ey}}{\partial y} \right|_{y=0}
$$

where $k_{sy}$ is equivalent spring constant at the center point of overlap. Fig. 5 illustrates the $k_{sy}$ and $k_y$ of a comb drive actuator with the folded-beams spring of 800 $\mu$m long, 4 $\mu$m wide, and 85 $\mu$m thick versus various static travelling distance. Due to the rotational moment, $(l_{overlap}/2 + l_0)^2/k_\theta$ in Eq. (8), the $k_{sy}$ is less than $k_y$ by more than 10 times. The rotational moment or the angular force effect herein, named as “the torsion effect” in the following discussion, will be further discussed in the next section, and the corresponding simulation results are calculated by FEM approach using ANSYS. Following the common definition in reference [1–3], $\left. \frac{\partial F_{sy}}{\partial y} \right|_{y=0}$ in Eq. (10) is defined as the critical spring stiffness $k_{ey}$, which is given as

![Fig. 5. The simulated $k_{sy}$ and $k_y$ of a folded-beams spring vs. static travelling distances.](image-url)
following the common used stability criteria of comb drive actuator, the ideal stable situation is at $\delta y = 0$ as shown in Fig. 6a, where $k_{s_y}$ is the spring stiffness of the normal folded-beam spring and attracted the rotor’s finger moving to the center axis and in contrast, if the deviation $\delta y$ exceeds the value of $y_{tolerance}$, the $F_{sy}$ is larger than the $F_{sy}$ and attracts the rotor’s finger moving to the center axis until the instability could still happen when $\delta y$ is over the value of $y_{tolerance}$.

That is why the measurement maximum static displacement usually less the calculated value.

On the other hand, when the process deviation is also consider in the stability criteria, the $F_{sy}$ demonstrated in Fig. 6b is further modified. The electrostatic force $F_{sy}$ in Eq. (3) can be rewritten as:

$$F_{sy} = \frac{1}{2} N_{\epsilon} t_{V}^2 \frac{\delta_{overlap}}{V^2} \left( \frac{1}{(g - \delta y)^2} - \frac{1}{(g + \delta y)^2} \right)$$

where $\Delta f$ is the central axis deviation due to the misalignment of fabrication process. Apparently, the force equilibrium point changes from $y_{tolerance}$ to $y_{tolerance}^\prime = y_{tolerance} + \Delta f$. That is, the robustness can be reduced by the process deviation. In theory, the maximum displacement occurs when the $\delta y$ approximately equals to $y_{tolerance}^\prime$. Thus, the force equilibrium at $y_{tolerance}^\prime$ in Fig. 6b can be given as:

$$k_{s_y} y_{tolerance}^\prime = \frac{1}{2} N_{\epsilon} t_{V}^2 \frac{\delta_{overlap}}{V^2} \left( \frac{1}{(g - y_{tolerance}^\prime)^2} - \frac{1}{(g + y_{tolerance}^\prime + \Delta f)^2} \right) - \frac{1}{(g + y_{tolerance} + \Delta f)^2}$$

Therefore, the overlap length $\delta_{overlap}$ can be given as:

$$\delta_{overlap} = \frac{L_0}{2} + \frac{2 y_{tolerance}^\prime k_{s_y}}{g \alpha - k_{s_y}}$$

where $\alpha = (1/(g - y_{tolerance}^\prime - \Delta f)^2 - 1/(g + y_{tolerance}^\prime + \Delta f)^2$ and $y_{tolerance}^\prime = y_{tolerance} + \Delta f$. According to Eq. (14), the $\delta_{overlap}$ will increase if the corresponding $k_{s_y}$ decreased and/or the corresponding $y_{tolerance}$ increased. In this paper, several new springs for comb drive actuators are designed to maintain the approximate $k_{s_y}$ as the value of conventional folded-beam spring, while the $k_{s_y}$ of the new springs is increased. The simulation results reveal that the $\delta_{overlap}$ becomes larger than the conventional comb drive with the folded-beams spring, i.e., denoted as the normal spring. Because the $k_{s_y}$ of the normal spring is decreasing while the $\delta x$ is increasing, the normal spring cannot sustain enough stiffness when $\delta x$ reaches large displacement area, such as $40 \mu m$ with respect to the spring length $1200$ and $4 \mu m$ gap between fingers. A tilted spring or compressive spring [9], in which its $k_{s_y}$ is increasing in proportional to the $\delta x$, was proposed to elevate the spring stiffness in $x$-direction with the same $k_{s_y}$ as the value of conventional folded-beam spring. However, the compressive spring is constrained by the geometric layout limit and the increasing torsion moment while the actuator structure is extended in scale for larger travelling space. Therefore, an advanced spring design is proposed to reduce the aforementioned torsion effect. This advanced design comprises a tilted spring and a normal folded-beams spring on both sides, i.e. the hybrid spring, and the normal folded-beams spring connected with an $n$-shaped joint. The simulation results in next section verify the comb drive with hybrid spring and
n-shaped joint can achieve larger $\delta_{\text{max}}$ than the ones with tilted spring and normal spring.

Nevertheless, the new stability criteria in this work have the vital issues about the unknown disturbances that are contributed by the various testing environment and fabrication deviation. Thus the disturbances cannot be specified in the following simulation results. The common used stability criteria, in which $k_y$ equals to $k_y$, in the case of $h_y = 0$, will still be utilized to compare the estimated $\delta_{\text{max}}$ of the new spring designs. Although the common used stability criteria can not precisely predict the maximum static travelling distance $\delta_{\text{max}}$, it is efficient enough to roughly estimate the value of $\delta_{\text{max}}$ for the comb drive actuator design or the spring performance. This new stability criterion is proposed herein to explain the real maximum static displacement $\delta_{\text{max}}$ that is less than the simulated value.

3. Results and discussions

3.1. Normal folded-beams spring versus tilted folded-beams spring

To basically reduce the instability influence from the moment contributed by the lateral electrostatic force of comb electrodes, all the spring anchors are assigned symmetrically at both sides of comb electrodes. The FEM is utilized to calculate the $k_y$ for different spring designs. A structure of 200 pairs of electrode fingers with 4 $\mu$m gap is adopted for all the comb drive actuators with different spring types. Referring to reference [9], the tilt spring design is proposed to obtain $\delta_{\text{max}}$ by 80 $\mu$m when the tilt projection length, i.e., $a$, in $x$-direction is 0.3 $\mu$m. However, even though the $k_y$ is elevating as the $s$-displacement increasing, the maximum travelling distance is restricted by torsion effect. Fig. 7a demonstrates the schematic drawings of comb drive actuators with the normal spring and tilted spring. As shown in Fig. 7a, due to the layout characteristics, the scale of $c$ and $d$ determine the displacement limit when the spring is compressed by electrostatic force, and the $dx$ limits the working distance of the comb electrodes, too. Different parameter combinations of $c$, $d$, and $dx$ regarding to the different displacement limits from 60 to 100 $\mu$m are listed in Fig. 7a. Fig. 7b demonstrates that the tilted spring with different parameters exhibits the approximately same $k_y$ with the folded-beams spring. In the case of $h_y = 0$ and with the same comb electrodes, Eq. (2) reveals that the $\delta_{s}$ of both the comb drive actuators with tilted spring and normal spring are under the same driving voltage. Therefore, according to Eq. (11), $k_y$ of the comb drive with normal spring is also approximately as same as the one with tilted spring. With the same $k_y$ shown in Fig. 7b and $c$, it indicates that the $k_y$ of normal spring is decreasing with the increment of $s$-displacement, and $k_y$ intersects the line of $k_{sy}$ at around $x = 44$ $\mu$m, while the $k_{sy}$ of tilted spring with different parameters are promoted with the increment of $s$-displacement. Moreover, based on Fig. 7a and $c$, the $k_{sy}$ of tilted spring is dramatically decreased for the increased values of $c$ and $dx$. Thus, due to the side sticking between electrodes, the maximum static $s$-displacement drops to 40 and 30 $\mu$m, when the displacement limit increased to 90 and 100 $\mu$m, respectively. Additionally the stiffness in $y$-direction is higher for the tilted springs having the smaller $c$ and $dx$. For these springs, without intersecting the line of $k_{sy}$, the maximum $x$-displacements are restricted by the working range limitation regarding to the geometric layouts. With the optimized parameters like spring length of 1200 $\mu$m, displacement limit of 87 $\mu$m, c of 27 $\mu$m, and $dx$ of 321 $\mu$m, the tilted spring will achieve the optimal maximum travelling distance around 83 $\mu$m as depicted in Fig. 7d. Fig. 7d also reveals that the $\delta_{\text{max}}$ of the comb drive with tilted spring is restricted by the displacement limit before it reach the optimal $x$-displacement with respect to the same $k_x$; once the displacement limit exceeds the value of optimal $x$-displacement, the $\delta_{\text{max}}$ of the comb drive with tilted spring will be decreased and limited by the torsion effect.

Referring to ref. [9], the stiffness $k_x$ of tilted spring in $y$-direction is given by:

$$k_x = \frac{600EI}{38s - 5d + 3a},$$

(15)

where $L_s$ is the projection of spring length in $y$-axis. Thus, the $k_x$ of tilted spring with different displacement limits are the same. Consequently, the dominant term in Eq. (8) is the term of $(600EI/2 + h_0)^2/k_0$, which is proportional to the values of $c$ and $dx$ in Fig. 7a, and is inversely proportional to the value of $k_0$. Therefore, the comb drive with tilted spring will be limited by the torsion effect when the travelling limit is increased. In order to reduce the torsion effect when the displacement limit distance is increased, half of the tilted spring is substituted by a folded-beam spring connected with a novel $n$-shaped joint. Such type of comb drive actuator comprising a tilted spring and a folded-beam spring with an $n$-shaped joint is named as hybrid spring type and will be discussed in next section.

3.2. Hybrid spring

For the comb drive with the tilted spring of 1200 $\mu$m and displacement limit of 87 $\mu$m, achieves the maximum static displacement, $\delta_{\text{max}}$, of 83 $\mu$m. Once the displacement limit is extended to 90 $\mu$m, the maximum $x$-displacement decreases to 40 $\mu$m or less. Referring to [9] and the simulation results shown in Fig. 8a, the value of $k_y$ of tilted spring always exceeds the $k_{sy}$ for the case of $s$-displacement less than 120 $\mu$m. Due to the torsion effect, the lateral stiffness of tilted spring is extremely deteriorated. In the other words, the $k_{sy}$ is much less than the $k_y$ of tilted spring and coincides $k_{sy}$ in small $s$-displacement area shown in Fig. 8a.

The $k_{sy}$ of folded-beams spring is also influenced by the torsion effect as shown in Fig. 8a and is much less than the $k_y$ of the same spring type. Nevertheless, the $k_{sy}$ of
Fig. 7. (a) Schematic diagrams of symmetric folded-beams spring and symmetric tilted spring; (b) Electrostatic force in x-direction of symmetric folded-beams spring and symmetric tilted spring with various displacement limits vs. x-displacement; (c) Simulated results of $k_s$ and calculated $k_y$ of the normal spring and the tilted springs with various travelling limits vs. the x-displacement; (d) The maximum static x-displacements vs. various displacement limits of tilted springs.
Fig. 8. (a) The simulated results of $k_{xy}$, $k_y$, and the calculated $k_{xy}$ of normal spring, tilted spring, hybrid spring without $n$-joint, and hybrid spring vs. the $x$-displacement; (b) Schematic layout drawing of hybrid spring without $n$-joint; (c) Schematic layout drawing of hybrid spring.

The analytical and simulation results of the hybrid spring without $n$-joint are derived based on spring length of 1200 $\mu$m, spring width of 3 $\mu$m, spring thickness of 85 $\mu$m, displacement limit of 120 $\mu$m, and $d$ of 30 $\mu$m. The simulation results reveal that the stiffness in moving direction is also equivalent to the folded-beams spring and tilted spring with the same spring length, i.e. 1200 $\mu$m, while the $k_{xy}$ of hybrid spring performs as the combination of folded-beam spring and tilted spring. However, the $k_{xy}$ of hybrid spring without $n$ joint is only slightly improved comparing to the $k_{xy}$ of tilted spring, and the torsion effect still dominates the $k_{xy}$ of the hybrid spring without $n$-joint.

To further reduce the torsion effect, a novel $n$-shaped joint connected with the folded-beams spring of hybrid spring is proposed as shown in Fig. 8c. Similarly, the stiffness in
x-direction of the hybrid spring connect with n-joint is also kept the same as the ones without an n-shaped joint. This hybrid spring with n-joint is denoted as "hybrid spring". The $k_y$ of hybrid spring with n-shaped joint can also be given as:

$$k_y = \frac{Ew^3}{2L_n} + \frac{100EI}{3L_n^3} + \frac{300EI}{(3d_l^2 - 5d_l^2)}$$ (17)

where the $L_n$, $w$, and $H$ are the length, the beam width, and the spacing between two beams of n-joint, respectively, as shown in Fig. 8c. Derived by $L_n = 1000\mu m$, $H = 11\mu m$ and beams width $= 5\mu m$, the $k_y$ of hybrid spring as shown in Fig. 8a is quite closed to the $k_y$ of hybrid spring without n-joint. Although the torsion effect still influences the $k_y$ of hybrid spring with an n-shaped joint over the small x-displacement range, the $k_y$ is getting closed to the $k_y$ as the x-displacement increasing. That is, the torsion effect is eliminated over the large x-displacement range, and the $k_y$ of hybrid spring without an n-shaped joint is sufficient to maintain the stability of comb drive actuator.

Fig. 9 interprets the $k_y$ of hybrid spring with an n-shaped joint of various lengths, beam widths, and the space distances between beams, i.e. $L_n$, $w$, and $H$. When $H$ increases from 11 to 33 $\mu m$, the $\delta_{\text{max}}$ decreases from 100 to 92 $\mu m$; while $L_n$ decreases from 1000 to 500 $\mu m$, the $\delta_{\text{max}}$ extremely drops from 100 to 22 $\mu m$. For the n-shaped joint design with different parameters, the beam width of the n-shaped joint does not change the results of $k_y$ of the hybrid spring; the smaller $H$ can provide the higher $k_y$ for the hybrid springs; and the $L_n$ should be large enough, i.e., larger than 850 $\mu m$ based on our simulation, to avoid the serious dropping of $k_y$ over small x-displacement area.

As shown in Fig. 10, regarding to the spring length of 1200 $\mu m$, spring width of 3 $\mu m$ and spring thickness of 85 $\mu m$, the simulation results reveal that the optimal maximum static x-displacement, $\delta_{\text{max}}$, of the comb drive with folded-beams spring is around 40 $\mu m$; while the optimal $\delta_{\text{max}}$ of the comb drive with tilted spring is about 80 $\mu m$. Finally, the x-displacement value of the comb drive with hybrid spring can further exceed the value generated by the tilted spring type. The simulation results in this paper can

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Fig. 9. Simulated results of the $k_y$ of hybrid spring with various n-joint types vs. the x-displacement.

Fig. 10. The simulated and optimized $k_y$ of the folded-beams spring, the tilted spring, the hybrid spring, and the calculated $k_y$ vs. x-displacement while the stiffness of all the spring types in x-direction are approximate 0.43 N/m~0.44 N/m.

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achieve more than 100 μm static displacement. The experimental study is under going.

4. Conclusions

In this paper, a new stability criterion for the general comb drive actuator with several of spring designs is proposed. Due to the torsion effect on the stability of the comb drive actuator with different spring types, using the $k_{sy}$, instead of $k_y$, as the major design parameter can provide the more accurate simulation results of the maximum static $x$-displacement. Based on the same stiffness in moving direction, the lateral stiffness of folded-beams spring, tilted spring, and hybrid spring with and without an $n$-shaped joint are discussed in this paper. The comb drive with the tilted spring can achieve the larger maximum static $x$-displacement than the one with the folded-beams spring. However, the torsion effect constrains the maximum static $x$-displacement of tilted spring. Therefore, the novel hybrid spring with an $n$-shaped joint not only increases the initial $k_{sy}$ of the tilted spring, keeping the superiority of the $k_{sy}$ of tilted spring, but also eliminates the torsion effect over large displacement area. Besides, such data also point out a factor that our new hybrid spring design (with $n$-joint) will not deteriorate the force output in moving direction, comparing with the other comb actuators. This is an important performance requirement to actuator too.

References


Biographies

Chihchung Chen received B.E and M.E. degrees in power mechanical engineering from National Tsing Hua University, Hsinchu, Taiwan in 1997 and 1999, respectively. He joined Asia Pacific Microsystems, Inc., Hsinchu, Taiwan, in 2001 and is now a research and design engineer, who engaged in developments and applications of MEMS actuator.

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