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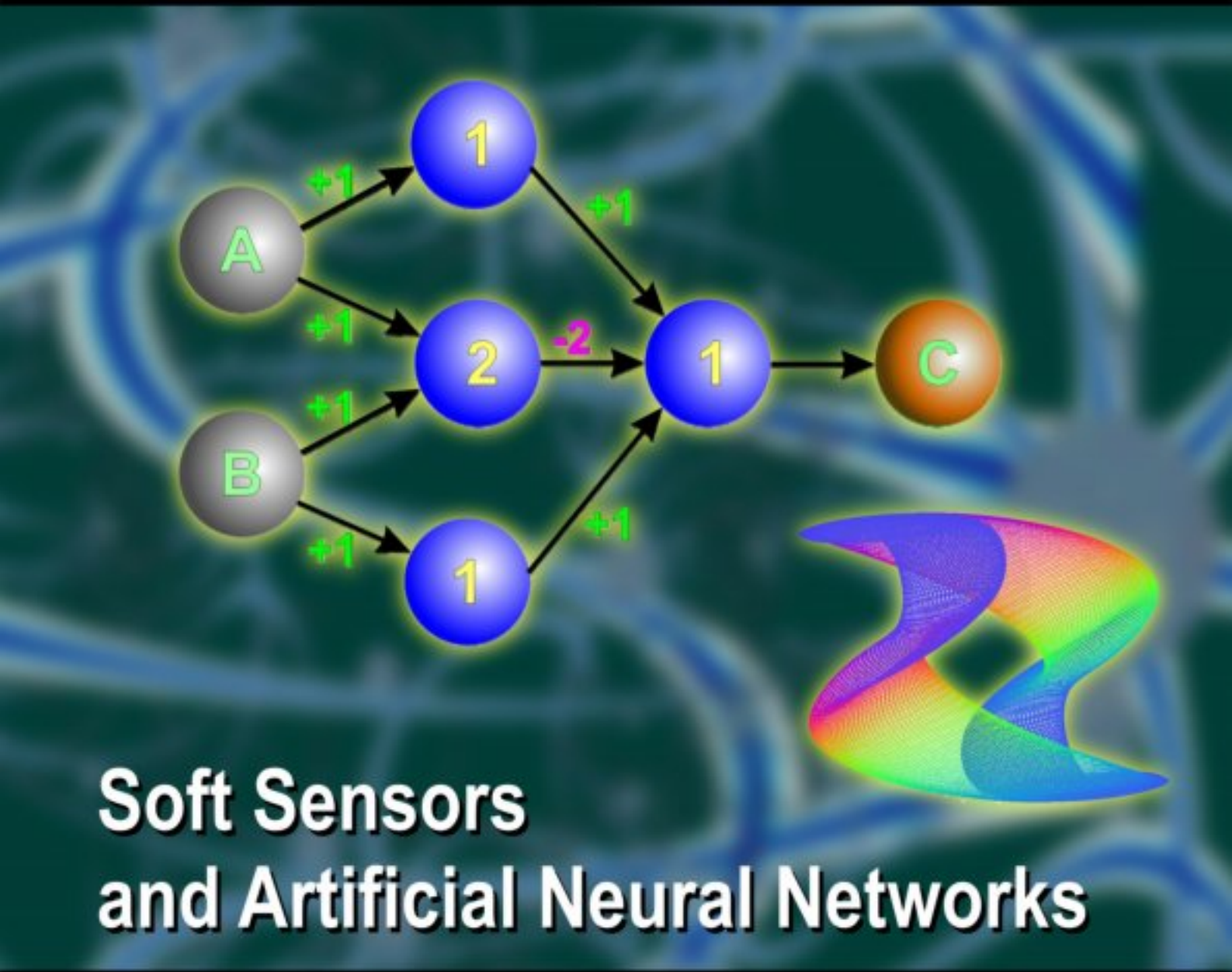


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**General Editor:** professor Nikolay V. Kirianaki, phone: +380 322 762971, e-mail: ifsa@sensorsportal.com
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# Optimized Design of Microresonators Using Genetic Algorithm

**G.Uma[1], A. Girija[2], M. Umapathy[3]**
[1, 2, 3] Department of Instrumentation and Control Engineering,
National Institute of Technology, Tiruchirappalli, India-620015
[1]E-mail: guma@nitt.edu
[3]E-mail: umapathy@nitt.edu

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**Abstract:** This paper represents the optimization of micro resonator design using Genetic Algorithm. Optimized physical layout parameters are generated using genetic algorithm. Optimization evaluates parameter by minimizing active device area, electrostatic drive voltage or a weighted combination of area and drive voltage or by maximizing displacement at resonance. Desired resonant frequency and mode frequency separations are governed by the objective function. Layouts are generated for optimized design parameters using Coventorware. Modal analysis is performed and it is compared with the designed resonant frequency.

**Keywords:** Microresonators; Genetic Algorithm; Resonant frequency

## 1. Introduction

Micro-Electro-Mechanical Systems (MEMS) are commonly defined as sensor and actuator systems that are made using integrated-circuit fabrication processes. The main advantage of MEMS-based systems when compared with conventional electromechanical systems is the miniaturization and integration of multiple sensors, actuators, and electronics at a low cost. MEMS design usually begins with high-level specifications that describe the desired behavior of devices [1]. Both the physical

configuration and geometries must be chosen such that the resulting device satisfies the design objectives and operating constraints In general, there are a number of design variables and complex trade-offs between different performance specifications. Therefore, it is difficult to design MEMS by hand.

The designer has two analysis choices: numerical simulation (e.g., finite-element analysis), and behavioral simulation. Numerical simulation involves self-consistent mechanical finite-element analysis coupled with electrostatic boundary element analysis. This requires much iteration by the designer with different values assigned to the device dimensions or other design variables in each iteration. The design procedure is, therefore, time consuming [2]. Also FEA cannot evaluate all the performance metrics of interest, or may be restricted to certain specific domains (like only mechanical analyses or only electrostatic analyses. Behavioral simulation can be accomplished using many different commercial tools, such as SPICE, MATLAB [3] and Saber [4]. Unfortunately, the construction of behavioral models for MEMS components is completely manual, requiring specific device expertise, which is often lacking in a system designer. No rapid design process is available today for MEMS. As a result, fabrication replaces simulation in the iterative loop. This is very expensive, since fabricated prototypes often do not meet performance specifications and, sometimes, are not even functional. Full verification of designs requires months of effort. Therefore the structured design of MEMS devices is essential. In this work structured design of MEMS device using genetic algorithm is presented.

Genetic algorithms are robust and efficient function optimizers, searching for the extremum of a given objective function [5]. Complex functions that often arise in the design work are highly non-linear, multimodal and nondifferentiable. Genetic algorithms allow us to search the design space in which the "best design" resides but whose form is not obvious or intuitive. The genetic algorithm search process is more efficient than trial-and-error methods, and has also been shown to outperform other search techniques such as gradient-based methods. As an example optimized design of microresonator using genetic algorithm is considered in this work. The optimized design variable values are validated using Coventorware.

## 2. Modeling of Micro Resonators

The microresonator shown in Figure 1 is used to describe design approach to MEMS component design. The specific resonator topology was first described and analyzed by Tang [6]. It is used in resonator oscillators, in filters [7], and as a mechanical characterization test structure to measure Young's modulus of thin films. The central shuttle mass suspended by two folded-beam flexures forms a mechanical mass-spring-damper system. The folded flexure is a popular design choice for the suspension because it is insensitive to buckling arising from residual stress in the polysilicon film. Instead of buckling, the beams expand outward to relieve the stress in the film.

The resonator can be fabricated by a surface-micromachining process MUMPS. The resonator is driven in the preferred (x) direction by electrostatic actuators that are symmetrically placed on the sides of the shuttle. Each actuator, commonly called a 'comb drive,' is made from a set of interdigitated comb fingers. When a voltage is applied across the comb fingers, an electrostatic force is generated which makes the structure to vibrate. The suspension is designed to be compliant in the *x* direction of motion and to be stiff in the orthogonal direction (y) to keep the comb fingers aligned.

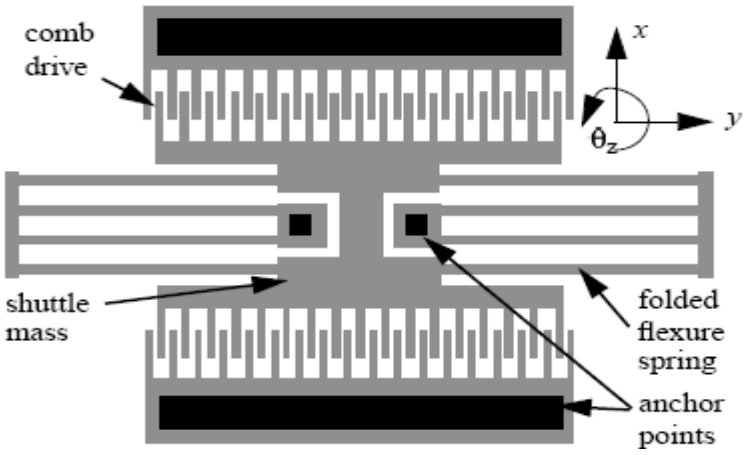



**Fig. 1**. Folded flexure comb drive resonator.

### 2.1 Modeling of the oscillation modes

In order to evaluate the performance of a design the models for the device behavior is needed. The preferred direction of motion of the micro resonator is the x-direction. However, the micro resonator structure can vibrate in other modes. Three translation modes along x, y and z and flexure modes are considered for modeling. Effective mass for each mode of interest is calculated by normalizing the total maximum kinetic energy of the spring by the maximum shuttle velocity, $v_{max}$

$$m_{eff} = \sum_{beam}^{N} \frac{m_i}{L_i} \int_0^{L_i} \left( \frac{v_i(\xi)}{v_{max}} \right)^2 d\xi$$

where $m_i$ and $L_i$ are the mass and length of the i'th beam in the flexure. Analytic expressions for velocities, $v_i$, along the flexure's beams are approximated from static deformation shapes, and are found from the spring constant derivations.

The net effective mass of the micro resonator in the x-direction ( $m_x$ ) can be written as

$$m_x = m_{shuttle} + m_{t,eff} + m_{b,eff}$$

where $m_{shuttle}$ is the shuttle mass, $m_{t,eff}$ is the effective mass of all truss sections, $m_{b,eff}$ is the total effective mass of all the beams.

The spring constant in the x direction is given by

$$k_x = \frac{2Etw_b^3}{L_b^3} \frac{L_t^2 + 14\alpha L_t L_b + 36\alpha^2 L_b^2}{4L_t^2 + 41\alpha L_t L_b + 36\alpha^2 L_b^2},$$

where E is the Young's modulus of polysilicon, t is the polysilicon thickness, and

$$\alpha = \left(\frac{w_t}{wb}\right)^3 .$$

Similarly the modeling equations for y, z and flexure modes can be derived and these are given in the technical report [2]. The total damping force in the x-direction is mainly composed of the forces due to Couette flow below the resonator, Stokes flow above the resonator, and airflow in the gap between comb fingers. The expression for the damping coefficient [8] is

$$B_x = \mu\left[\left(A_s + 0.5A_t + 0.5A_b\right)\left(\frac{1}{d} + \frac{1}{\delta}\right) + \frac{A_c}{g}\right]$$

where $\mu$ is the viscosity of air ($1.8\times10^{-5}\ Ns/m^2$), d is the fixed spacer gap between the ground plane and the bottom surface of the comb fingers, $\delta$ is the penetration depth of airflow above the structure, g is the gap between comb fingers, and $A_s, A_t, A_b$ and $A_c$ are layout areas for the shuttle, truss beams, flexure beams and comb finger sidewalls, respectively.

General analytic equations for the lateral comb drive force, $F_x$, as a function of comb finger width $w_c$, air gap between comb fingers g, structure thickness t, and sacrificial spacer thickness d, are derived in [9]. For the special case of equal comb finger width, gap, thickness, and spacing above the substrate $(w_c = g = t = d)$, each comb drive generates a force that is proportional to the square of the voltage, V, applied across the comb fingers.

$$F_x \cong 1.12\varepsilon_0 N\frac{t}{g}V^2$$

where $\varepsilon_0$ is the permittivity of air, N is the number of fingers in the movable comb drive, V is the instantaneous voltage across the comb fingers. If the comb fingers are not perfectly centered, a y-directed electrostatic force is also present. In the absence of restraining springs, this force will result in snapping of the movable comb fingers and the stationary comb fingers. Assuming a small perturbation $\delta y$ in the y direction, the destabilizing force, $F_{e,y}$ is proportional to displacement such that $F_{e,y} = K_{e,y}\delta y$, where $k_{e,y}$ is an electrical negative spring constant.

$$k_{e,y} = 2\varepsilon_0 NV^2 x_0 \frac{t}{g^3}$$

If there is a small rotation $\delta\theta$, about the z-axis, a destabilizing electrostatic torque, $\tau_{e,\theta} = k_{e,\theta}\delta\theta$ is generated by the comb drive. The rotational spring constant is found by realizing that the destabilizing force acts through a moment arm, $X_c$, on the center of the resonator, giving

$$k_{e,\theta} = k_{e,y}X_c^2 \cong= 2\varepsilon_0 NV^2 x_0 \frac{t}{g^3}X_c^2,$$

where $X_c = 0.5L_{sa} + w_{cy} + L_c - 0.5x_0$.

## 3. Optimization Problem Formulation

Formulation of optimization problem involves determining the design variables, the numerical design constraints, and the quantitative design objective. The synthesis is achieved through an optimization algorithm, which seeks to minimize a cost function and simultaneously satisfy the constraints. Fifteen design variables are identified for the proposed micro resonator structure. The design variables are listed in Table 1 and shown in Figure 2. These include 13 geometrical parameters, the number of fingers in the comb drive N, and the effective voltage V. The voltage V equals $\sqrt{2V_{ac}V_{dc}}$ where $V_{dc}$ represents dc voltage applied to the shuttle, and $V_{ac}$, indicates the sinusoidal voltage applied to one side of comb drive actuator. Technology driven design rules set minimum widths and minimum spaces between structures. Maximum beam lengths are constrained to $400\mu m$ to avoid problems with undesirable curling due to stress gradient in the structural film and possible sticking and breakage during the wet release etch. Maximum width of beams is constrained to $20\mu m$ by the limited undercut of PSG to release the structures. The shuttle axle, the shuttle yoke and the comb yoke are at least $10\mu m$ wide so that, they are relatively more rigid than folded – flexure beams.

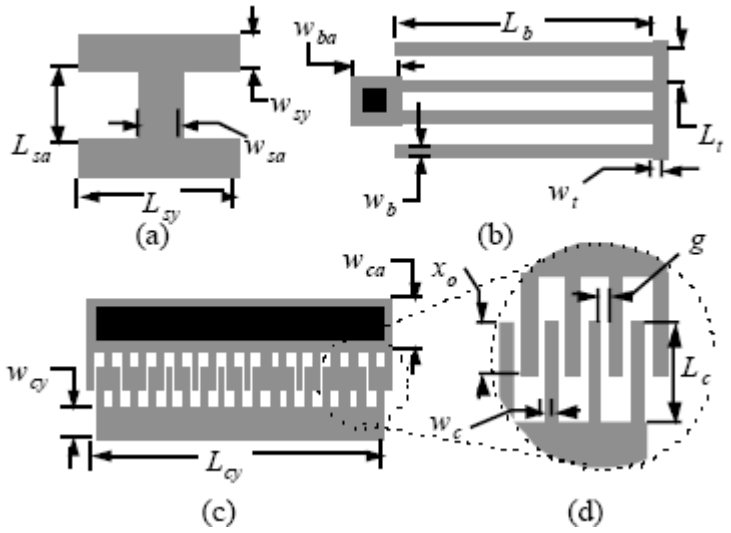



**Fig. 2.** Dimensions of the micro resonator elements: (a) shuttle mass, (b) folded flexure, (c) comb drive with N movable 'rotor' fingers, (d) close up view of comb fingers.

### 3.1 Geometric and functional constraints

The constraints can be classified into two kinds: geometrical constraints, which are directly related to the physical dimensions of the micro resonator and functional constraints, which are related to the behavior of the micro resonator. The constraints are detailed in Table 2. The resonator width and length must not exceed an arbitrary fixed size, set at $700\mu m$.

**Table 1.** Design Variables.

| **Design variables** | | | |
|---|---|---|---|
| **Variables** | **Description** | **Min** | **Max** |
| L | Length of flexure beam | 2 | 400 |
| $W_b$ | Width of flexure beam | 2 | 20 |
| $L_t$ | Length of truss beam | 2 | 400 |
| $W_t$ | Width of truss beam | 2 | 20 |
| $L_{sy}$ | Length of shuttle yoke | 2 | 400 |
| $W_{sy}$ | Width of shuttle yoke | 10 | 400 |
| $W_{sa}$ | Width of Shuttle axle | 10 | 400 |
| $W_{cy}$ | Width of comb yoke | 10 | 400 |
| $L_{cy}$ | Length of comb yoke | 2 | 700 |
| $L_c$ | Length of comb fingers | 8 | 400 |
| $W_c$ | Width of comb fingers | 2 | 20 |
| g | Gap between comb fingers | 2 | 20 |
| $x_0$ | Comb finger overlap | 4 | 400 |
| N | Number of comb fingers | 1 | 100 |
| V | Voltage amplitude | 1 | 50 |
| **STYLE VARIABLES** | | | |
| $W_{ba}$ | Width of beam anchors | 11 | 11 |
| $W_{ca}$ | Width of stator comb anchors | 14 | 14 |

**Table 2**. Geometric Constant.

| **Constraint Description** | **Expression** | **Min** $[\mu m]$ | **Max** $[\mu m]$ |
|---|---|---|---|
| Actuator length | $L_{cy} + 2g + 2w_c$ | 0 | 700 |
| Comb- fill | $(2N+1)w_c + 2Ng$ | $L_{cy}$ | $L_{cy}$ |
| Flexure length | $L_{sy} + 2L_b + 2w_t$ | 0 | 700 |
| Total resonator width | $3L_t + w_{sy} + 4L_c - 2x_0 + 2w_{cy} + 2w_{ca}$ | 0 | 700 |
| Comb clearance during motion | $L_c - (x_0 + x_{disp})$ | 4 | 200 |
| Minimum comb overlap | $x_0 - x_{disp}$ | 4 | 200 |
| Shuttle clearance during motion | $L_t - x_{disp} - (w_{sy} + w_b)/2$ | 4 | 200 |
| Shuttle gap in y | $(L_{sy} - 2w_{ba} - w_{sa})/2$ | 2 | 200 |

The functional design constraints are listed in Table 3. The resonant frequency constraint ensures that the user specification on frequency ( $f_{spec}$ ) is met. The next two constraints ensure that the resonator moves adequately at resonance and has a quality factor greater than 5, respectively. The mode decoupling constraints are necessary to ensure that the x-mode resonant frequency dominates. The three in-plane resonant frequencies $f_i$ are constrained to be at least thrice that of the x-mode while the out-of-plane resonant frequencies ($f_o$) are constrained to be at least twice that of the x-mode. For stability, the restoring force of the spring in the y direction must be three times greater than the destabilizing electrostatic force from the comb drive (i.e., $3k_{e,y} < k_y$). A similar stability constraint must hold for the rotational mode.

**Table 3**. Functional constraints.

| Constraint Description | Expression | Min | Max |
|---|---|---|---|
| Resonant frequency | $f_x / f_{spec}$ | 0.98 | 1.02 |
| Stroke at resonance | $x_{disp}$ | 2 μm | 100 μm |
| Quality factor in x | $Q_x$ | 5 | $10^5$ |
| y-axis stability | $k_{e,y} / k_y$ | 0 | 1/3 |
| $\theta_z$ stability | $k_{e,\theta z} / \theta z$ | 0 | 1/3 |
| In-plane mode separation | $f_x / f_i$ | 0 | 1/3 |
| Out-of –plane separation | $f_x / f_0$ | 0 | 1/2 |
| $k_x$ accuracy | $x_{disp} / L_b$ | 0 | 1/10 |

## 4. Optimization Using Genetic Algorithm

Three objective functions are chosen to minimize: total resonator active area, amplitude of the comb-drive voltage, and the sum of active area and drive voltage, and the sum of active area and drive voltage normalized to the maximum possible area and voltage; and a fourth objective function to maximize: displacement at resonance.

The general non-linear constrained optimization formulation can be written as

$$\min \ uz = \sum_{i=1}^{k} w_i f_i(u, x)$$

$$\min \ uz = f(u, x),$$

such that

$$h(u, x) = 0$$

$$g(u, x) \leq 0$$

$$u \in U_P,$$

where u is the vector of design variables given in Table 1; x is the vector of state and style variables; f(u, x) is objective function that codify performance specifications the designer wishes to optimize, e.g., area; and $h(u, x) = 0$ and $g(u, x) \leq 0$ are each a set of functions that implement the geometric and functional constraints given in Tables 2 and 3 .The constrained problem is solved by using genetic algorithm. Genetic algorithms are adaptive methods, which may be used to solve search and optimization problems.

Before a genetic algorithm can be run, a suitable encoding (or representation) for the problem must be devised. A fitness function is also required, which assigns a figure of merit to each encoded solution. During the run, parents must be selected for reproduction, and recombined to generate offspring.

It is assumed that a potential solution to a problem may be represented as a set of parameters. These parameters (known as genes) are joined together to form a string of values (chromosome). In genetic terminology, the set of parameters represented by a particular chromosome is referred to as an individual. The fitness of an individual depends on its chromosome and is evaluated by the fitness function.

The individuals, during the reproductive phase, are selected from the population and recombined, produced offspring, which comprise the next generation. Parents are randomly selected from the population using a scheme, which favours fitter individuals. Having selected two parents, their chromosomes are recombined, typically using mechanisms of crossover and mutation. Mutation is usually applied to some individuals, to guarantee population diversity. Figure 3 gives a flow chart for the basic genetic algorithm.

For optimized parameter generation using genetic algorithm, coding is developed using Matlab. The initial population is randomly generated for 16 design variables whose values are bounded within minimum and maximum specification given in Table 1. The geometric (Table 2) and functional (Table 3) constraints are checked with randomly generated chromosome. If all the constraints are satisfied, objective function is evaluated. Roulette wheel selection technique is used to select good string from the initial population. The following parameters are used for GA coding: 15-gene chromosome, population size=20, number of generations =50, Selection scheme=Roulette wheel, mutation probability $p_{mutation} = 0.05$, Crossover probability $p_{crossover} = 0.8$.

Resonators are synthesized using all five objective functions ranging from 14 kHz to 300 kHz. From the optimized results, it is clear that parameter synthesis explore a different region of the design space, leading to the diverse layouts based on the selection of objective function. Selected design parameters for the synthesized resonators with maximized displacement are shown in Figure 4. Optimized dimensions of micro resonator for frequency 36 kHz with maximized displacement as objective function is given in Table 4.

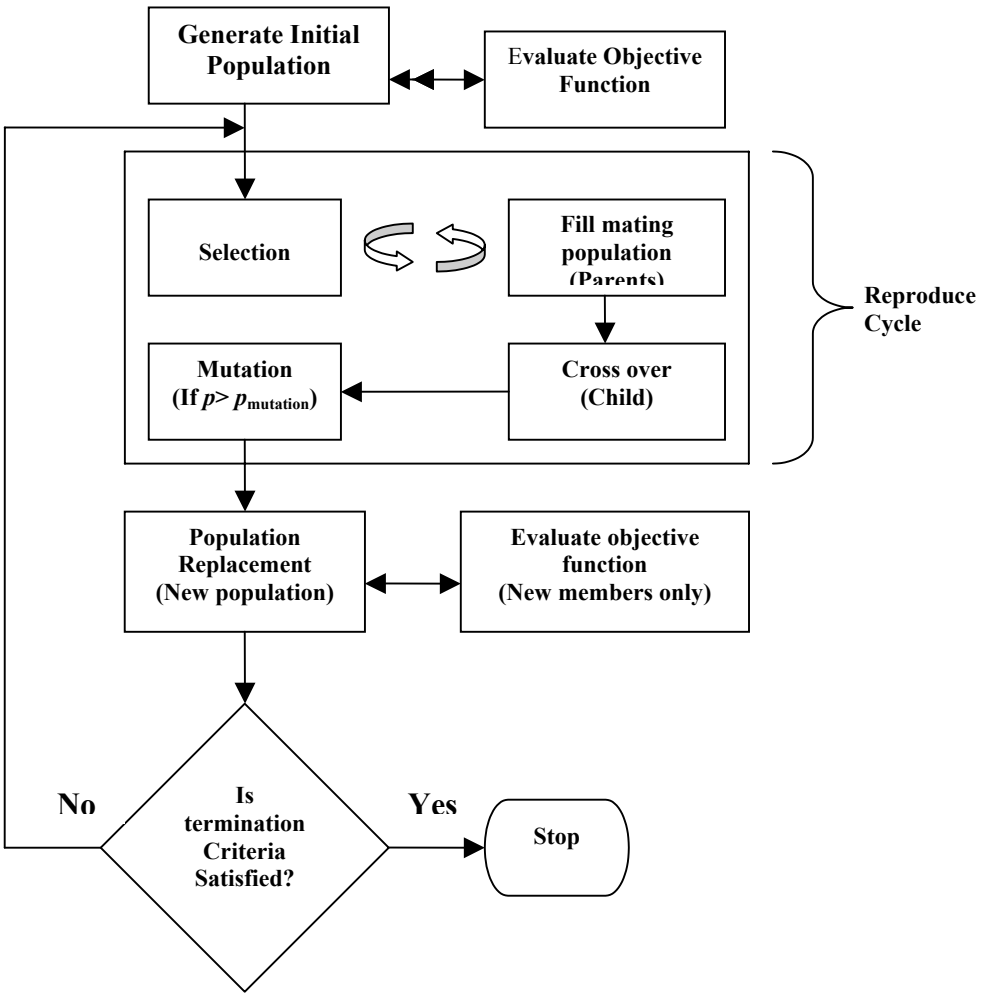



**Fig. 3.** Basic Genetic Algorithm flowchart.

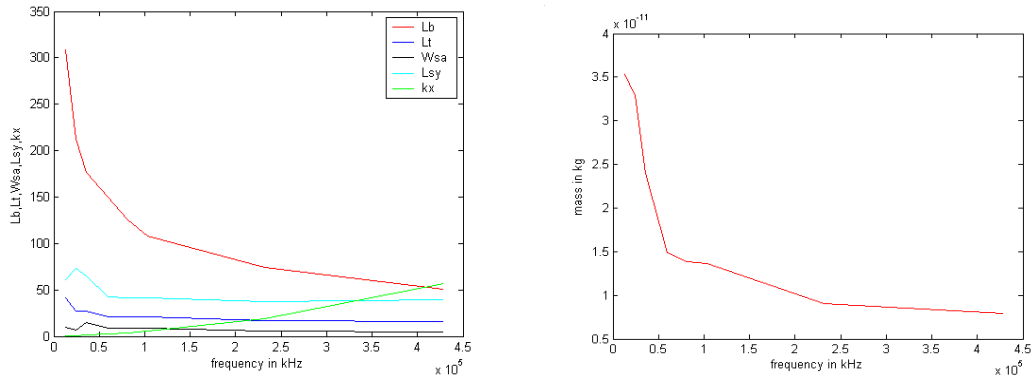



**Fig. 4.** Selected Parameter values for synthesized resonators with maximized displacement.

**Table 4.** Optimized dimensions of micro resonator for frequency 36kHz.
All units are in μm except voltage.

| | | | |
|---|---|---|---|
| Length of flexure beam | 176.53 | Length of comb yoke | 312.25 |
| Width of flexure beam | 2.03 | Length of comb fingers | 88.61 |
| Length of truss beam | 28.71 | Width of comb fingers | 2.5 |
| Width of truss beam | 11.01 | Gap between comb fingers | 2.5 |
| Length of shuttle yoke | 65.48 | Comb finger overlap | 60.85 |
| Width of shuttle yoke | 11.61 | Number of comb fingers | 31 |
| Width of Shuttle axle | 14.37 | Voltage amplitude | 44 |
| Width of comb yoke | 13.63 | | |

## 5. Design Validation Using Coventorware

The synthesis results are evaluated by comparing the predicted behavior to finite element analyses. From optimized results micro resonator layout is created using 2-D layout Editor and 3D model of the same is built by 3-D builder in CoventorWare. The finite element analysis of the designed structure is carried out using MemMECH module by using Manhattan type of meshing with element size of 2μm x 2μm x 4μm, which is found to be optimized mesher setting.

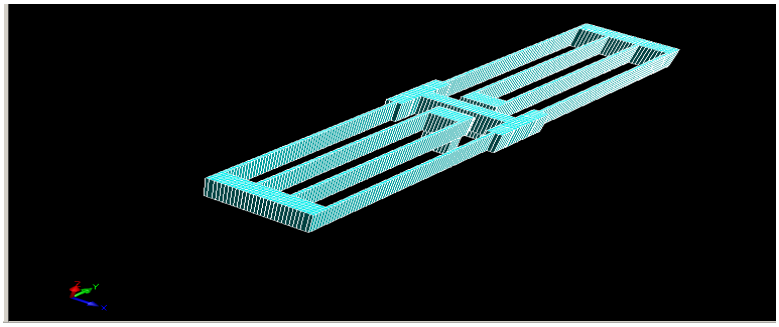


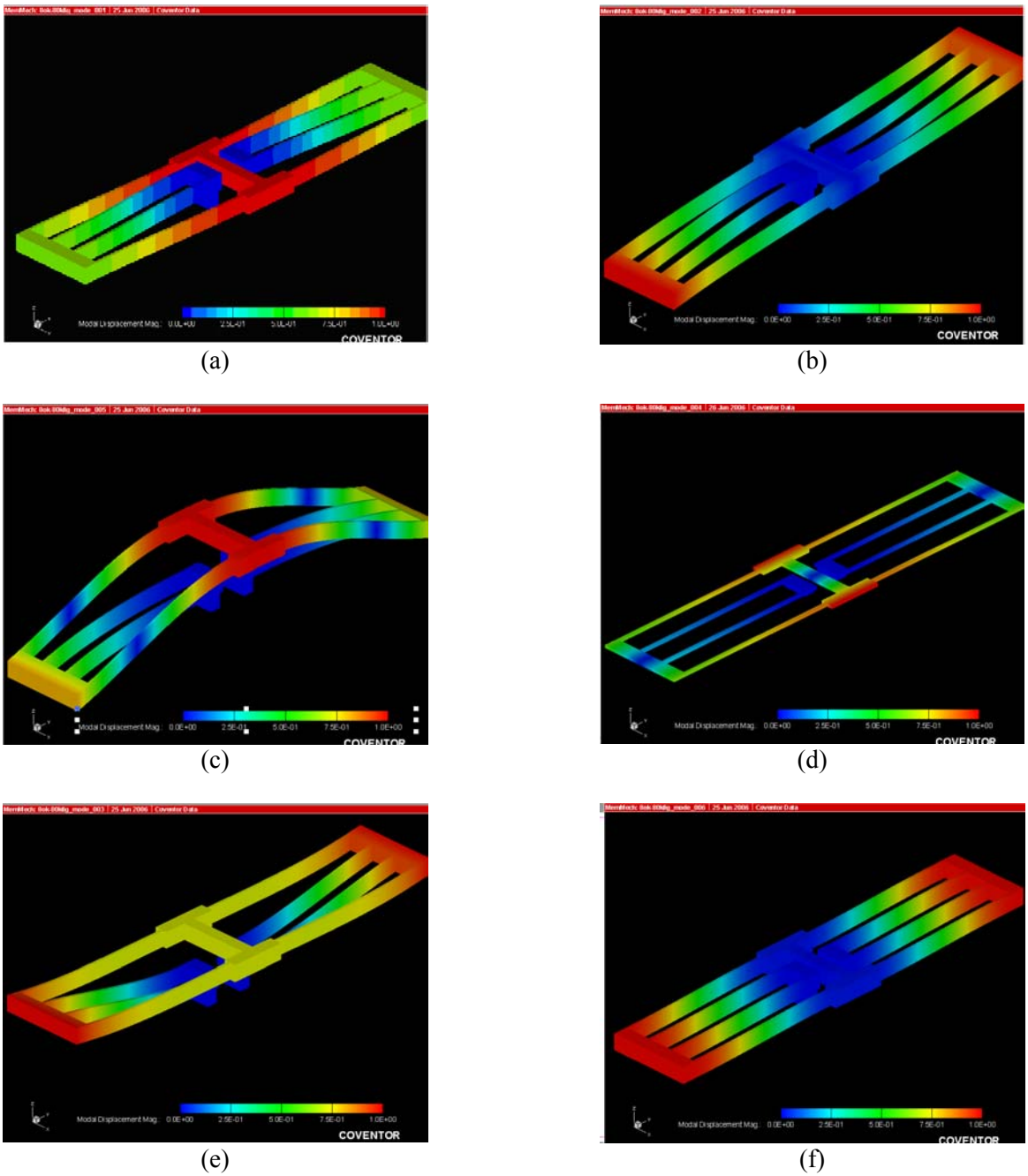
**Fig. 5**. Meshed model.

The modal analysis is used to find the natural frequency of the structure. Table 5 shows the modal frequencies from MemMech analysis for the layout designed for 79 kHz. The mode shapes represent the overall deformation of the proof mass oscillating at the associated modal frequency. Modal shapes for the first six modes are shown in Figure 6. The first and third mode is the translation mode along x and z-axis respectively. Fourth mode is rotational mode along x-axis and sixth mode is anti flexural mode. The preferred direction of motion of the micro resonator is along x-axis. From modal analysis results, it is clear that the objective is satisfied since it is the first mode.

The synthesized microresonators were simulated with Coventorware using 3D beam elements and the frequencies of modes were compared to the frequencies predicted by the analytical models.

**Table 5**. Modal analysis Results.

| S. No | Frequency | Generalized mass |
|---|---|---|
| 1 | 7.4415e04 | 1.5e-11 |
| 2 | 7.762717e04 | 9.578e-12 |
| 3 | 7.888452e04 | 1.5387e-11 |
| 4 | 1.221104e05 | 7.89978e-12 |
| 5 | 1.359506e05 | 1.34889e-11 |
| 6 | 1.55624e05 | 1.164308e-11 |




(a) (b) (c) (d) (e) (f)

**Fig. 6.** Mode shapes (a) mode1 (b) mode 2 (c) mode3 (d) mode 4 (e) mode 5 (f) mode 6.

Comparison of simulated and designed frequency values of x, z and flexure mode is given in Table 6.

**Table 6**. Desired and simulated frequency values.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| fx spec | 1.31e04 | 2.4e04 | 3.8e04 | 5.8e04 | 8e04 | 1e05 | 2.2e05 | 4.2e05 |
| fx sim | 1.25e04 | 2.3e04 | 3.5e04 | 5.6e04 | 7.4e04 | 9.7e04 | 2.0e05 | 3.8e05 |
| fz spec | 1.63e04 | 2.9e04 | 4.7e04 | 7.2e04 | 9.9e04 | 1.2e05 | 2.7e05 | 5e05 |
| fz sim | 1.41e04 | 2.8e04 | 3.8e04 | 6.141e04 | 7.8e04 | 1.0e05 | 2.1e05 | 4.1e05 |
| fflspec | 3.39e04 | 6.9e04 | 9.8e04 | 1.48e05 | 2.0e05 | 2.5e05 | 5e05 | 1e06 |
| fflsim | 2.98e04 | 6.8e04 | 7.9e04 | 1.22e05 | 1.6e05 | 2.0e05 | 4.8e05 | 9.2e05 |

From the table it is seen that the simulated and specified frequency values from 14kHz to 300kHz are nearly equal. Layouts are synthesized for the above frequency range with minimized area and maximum displacement as objective junction. From Figure 7 and 8 it is observed that the resonators become smaller with increasing values of resonant frequency. Smaller devices have less mass, and smaller flexures are stiffer. Increasing the resonator frequency requires an increase in stiffness, $k_x$ which can be accomplished using shorter beams $L_b$.

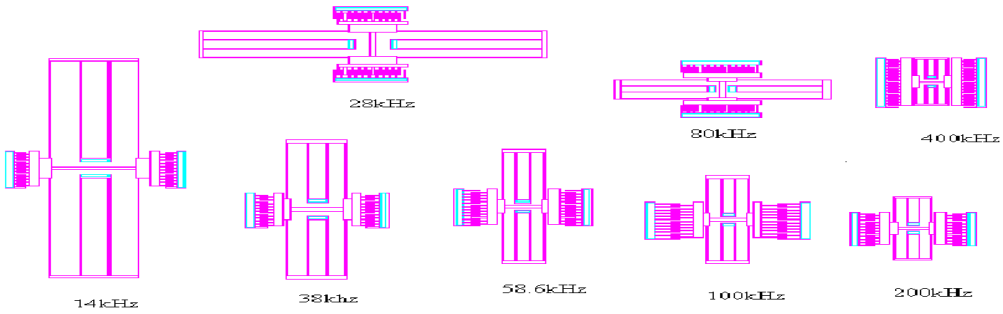



**Fig. 7.** Layout synthesized using coventorware with minimized area as objective function.

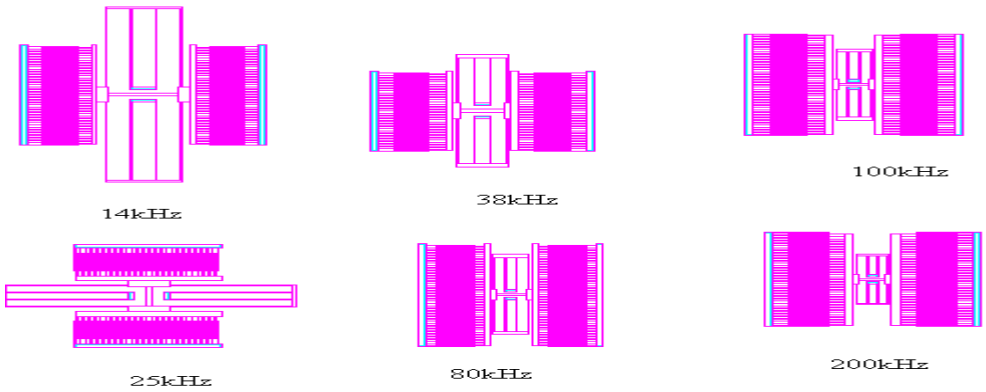



**Fig. 8.** Layout synthesized with maximum displacement as objective function.

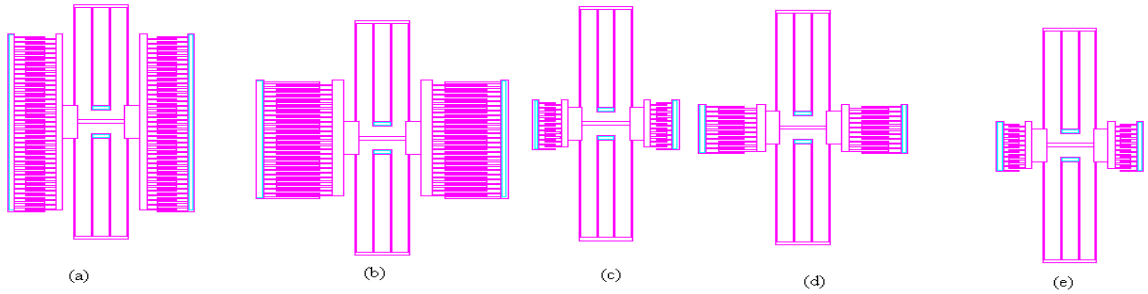



**Fig. 9.** Comparison of layouts synthesized for 13kHz frequency for different objective function: (a) Minimum voltage; (b) Maximum displacement; (c) Minimum area; (d) Multi objective; (b) (e) Normalized sum of active area and voltage.

Electrostatic actuation with low driving voltage is an important design specification in microresonator design. Driving voltage can be minimized by increasing the number of fingers. For obtaining maximum displacement the length of the finger should be more since the displacement is high. Furthermore, the minimum area resonators tend to have the fewest fingers, sum of area and voltage resonators tend to trade off between fingers and drive voltage. From Figure 9 it is seen that simulated layout for minimum voltage has more fingers, minimum area with fewer fingers and maximum displacement with longest fingers.

## Conclusion

Optimal design of folded flexure electrostatic comb drive micro resonator models is successfully done using genetic algorithm. Optimization problem is formulated with all necessary design variables, constraints and for different objective functions. The in-plane and out of plane mode separation constraints ensure that the other modes of vibration are well separated from the x-mode of vibration. The nonlinear constrained optimization problem is solved using genetic algorithm. The genetic algorithm search process is more efficient than traditional methods, and has also been shown to out perform other search techniques such as gradient-based method. Layouts are synthesized for 14 kHz to 300 kHz frequency range in Coventorware using optimum parameter values. MemMech analysis is used to simulate the mechanical behavior of the micro resonators. The specified resonant frequency and simulated resonant frequencies for x, z and flexural modes are compared.

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