Genetic Algorithm Tuned Microelectromechanical Filters using Polysilicon Comb Microresonators

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Summary
Microelectromechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilization of microfabrication technology(1,4). These filters consist of miniature mechanical vibrating elements such as capacitively coupled beams or thin-film bulk acoustic resonators. In this paper, the design of a microelectromechanical series bandpass filter is done by (i) first designing a digital bandpass filter of transfer function H(z), (ii) tuning the digital BPF for minimum order and minimum MSE in the pass-band and stop-band using the Genetic algorithm (GA), (iii) relating the tuned digital BPF coefficients with the microelectromechanical filter geometry parameters, (iv) realizing the resultant microelectromechanical filter structure and (v) finally obtaining the frequency response of the microelectromechanical filter. The parameters are tuned using GA to have high Q values. The obtained frequency response of the designed filter promises good performance over the operating frequency range. The different factors that influence the performance of the filter are also discussed in the paper. The obtained frequency response shows that the parameter optimization process is invariant as the coefficients are transformed from the digital to the microelectromechanical domain.

Key words:
Digital BPF, Microelectromechanical filters, Resonators, Coupled beams, Genetic algorithm.

Nomenclature
M_{ip} , M_{ib} : Mass of the plate and the folded beams (of the i^{th} resonator) in gms
w_i , l_i : Width and Length of the struts in folded suspensions in ⟨m
h : thickness of the microstructure in µm
E_p : Young's modulus of polysilicon in Gpa
Q_i : Quality factor
k : Spring stiffness
M_i : Mass of the plate in gms
N: number of comb fingers
α: transformation parameter
V_{pi} :dc bias at the input port
V_{po} : dc bias at the output port
F_{mi} : balancing force due to the resonator having mass M_i
F_{Di} : balancing force due to the i th Damping coefficient
F_{ki} : balancing force due to the k^{th} Spring element connected to i^{th} mass element
F_{ki} : balancing force due to the k^{th} Spring element connected between i^{th} and j^{th} mass elements
ϕ_i : Amplification factor
X_n : output displacement or signal
F: input force or excitation
L_i : inductance of a comb-driven resonator
R_i : resistance of the comb-driven resonator
C_i : capacitance of the comb-driven resonator.

1. Introduction

The term MEMS refers to a collection of micro-sensors and actuators, which can sense its environment and react to changes in that environment with the use of a microcircuit control(1). These include, in addition to the conventional microelectronics packaging, integrated antenna structures for command signals. The system also may need micro power supply, micro relay and micro signal processing units. Micro components make the system faster, more reliable, cheaper and capable of incorporating more complex functions(2). In the beginning of the 1990s, MEMS emerged with the aid of the development of integrated circuit (IC) fabrication processes, where sensors, actuators and control functions are co-fabricated in silicon. In addition to the commercialization of some less-integrated MEMS devices, such as micro-accelerometers, inkjet printer heads, micro mirrors for projection, etc., the concepts and feasibility of more complex MEMS devices for the applications in such varied fields as micro-fluidics, aerospace, biomedicine, chemical analysis, wireless communications, data storage, display, optics etc. remains largely unexplored. Most MEMS devices with various sensing or actuating mechanisms are fabricated using silicon bulk micro-machining, surface micro-machining and LIGA1 processes(3). Three dimensional micro-fabrication processes incorporating more materials have been proposed for MEMS recently with some specific application requirements (e.g. biomedical devices). In this paper, microelectromechanical filters based on coupled

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lateral microresonators are presented. A series microelectromechanical filter model based on mechanically coupled polysilicon comb microresonators is proposed. The parameters governing the filter geometry are tuned using the genetic algorithm technique for improved response. The objective function in GA was aimed at providing a filter with a (i) narrow bandwidth (high Q), (ii) good signal-to-noise ratio and (iii) stable temperature and aging characteristics.

2. Mechanical Filter Model

The series mechanical filter model is illustrated in the figure 1. The springs kij links two adjacent resonators, each having (i) masses Mi and Mj and (ii) springs ki and kj.. The factors that influence the frequency reponse of the filter shown, are (i) resonators, (ii)coupling springs and (iii) bridging springs which link non-adjacent resonators. This implies, that, higher order systems with multiple-coupling springs can enable the synthesis of high-quality bandpass filters. The structure shown converts the electrical signals at input (using electromechanical transducer) into mechanical vibrations, pass through the series filter and then convert the filtered output back into electrical signals (using an output electromechanical transducer). Conventional mechanical filters use magnetostrictive and piezoelectric transducers. The transfer function of the mechanical filter model is easily obtained as (see appendix-I)

$$X_2(s)/F(s) = k_{12} / \{[M_1 M_2]s^4 + [M_1 D_2 + M_2 D_1]s^3 + [(k1 + k_{12}) M_1 + (D_1 D_2 + M_2 (k_1 + k_2)]s^2 + [D_2 (k_1 + k_{12}) + D_1 (k_2 + k_{12})]s + [k_1 k_2 + k_{12} (k_2 + k_1)]\} \quad \text{---- (1)}$$

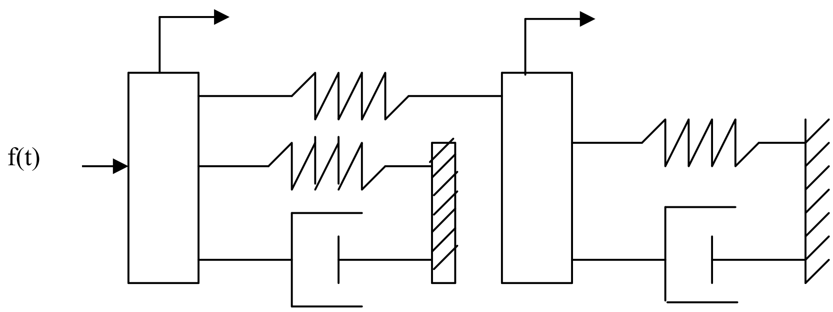

Fig. 1 Mechanical model of a series N-resonator filter

3. Electrical Filter Model

The electrical equivalent circuit of the filter is shown in figure 2. The transfer function of the filter is easily obtained as (see appendix-II) where G2n and G2n-1 ……G0 are constants and are functions of the filter geometry. It can be observed, that the electrical and mechanical elements are related as

$$I_0 / V_i = \frac{j\omega V po\ V pi\ (\partial C/\partial x)_i\ (\partial C/\partial x)_o}{G_{2n} (j\omega)^{2n} + G_{2n-1} (j\omega)^{2n-1} + G_{2n-2} (j\omega)^{2n-2} \ldots\ldots + G_0}$$

$L_i = M_i\,\alpha^2$; $C_i = 1/(k_i\,\alpha^2)$ and $R_{ij} = 1/(k_{ij}\,\alpha^2)$ ----(2)

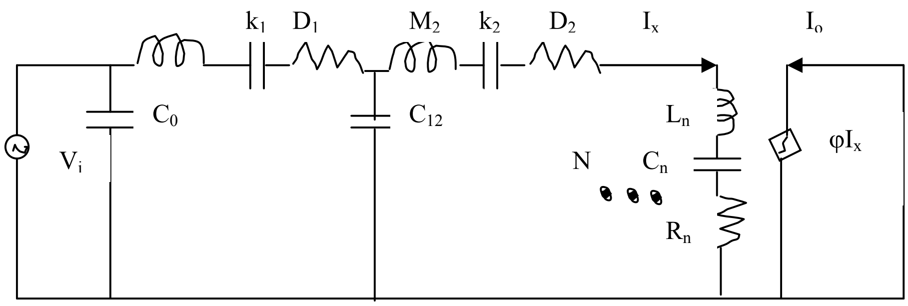

Fig. 2 Electrical equivalent circuit of the filter

4. Electromechanical Filter Model

In the elctromechanical model, the electrical outputs of multiple microresonators with resonance frequencies differing by a specific desired amount are combined. Bandpass and notch electromechanical filters are very common (3). For the case of bandpass filters, it is necessary to ensure that the relative phase difference between microresonators is selected such that electrical signals combine in the interval when the signals are in phase and subtract when they are approximately 1800 out of phase.

5. Factors Influencing Filter Performance

The following factors are found to influence the performance of the filter:
(1) Filter dimensions i.e. the geometrical changes made in the folded beam resonators,
(2) Quality factor, which may change with frequency for a given material,
(3) Series motional resistance,
(4) Absolute and matching tolerances of resonance frequencies and
(5) Stability of the resonance frequency against temperature variations, mass loading, aging and other environmental phenomena.

6. Digital Bandpass Filter

A generalized digital filter is given by the transfer function

$$H(Z) = \frac{K\,(Z+a)\,(Z^2+a_1 Z+a_2)}{(Z+b)\,(Z^2+b_1 Z+b_2)} \qquad \text{------(3)}$$

Different types of filter structures such as Low pass, High pass, Band pass and Band stop of different order can be obtained by suitably defining the filter coefficients in eqn. (3). In this work, a digital BPF is chosen and the filter was tuned for a minimum order and in MSE sense using genetic algorithm.

7. GA Coding Scheme

The Genetic Algorithm was used to tune the coefficients of the digital BPF since it offers certain intrinsic advantages such as (i) no mapping between analogue-to-digital, (ii)multi-objective functions can be simultaneously solved and (iii)a guaranteed stable lower order filter is obtained(5). The coding scheme employed consists of two blocks, the control block and the coefficient block. The control block determines whether a particular coefficient is selected or de-selected, while the coefficient block determines the actual value of the coefficient. Sufficient trials were performed and finally the following filter coefficients K=0.0386; b1=0.0380; b2=0.8732; a1=1.3628; a2=0.7122; b=0.6884 and a=0.6580 were found to give a (i)stable filter performance (ii)lower filter order and (iii)minimum mean square error in the pass-band and stop-band.

8. Relating Digital Filter Coefficients and Filter Geometry

From the digital filter transfer function of eqn.(3), the filter coefficients can be equated with the microelectromechanical filter geometrical parameters of a first order series resonator, to get (appendix-III) (i) M1=0.85, (ii) k1=0.65, (iii) D1=22.3, (iv) M1b=M1p=0.62, (v) w1=1.54, (vi) l1=150, (vii) h1=2 and (vi) Ep=150.

9. Simulation Results

The response of the microelectromechanical filter with the filter geometry given above was obtained in the ANSYS software tool and is shown in figure 3. Two such resonators in cascade gave a response shown in figure 4. The obtained response matches well with the response of an ideal BPF.

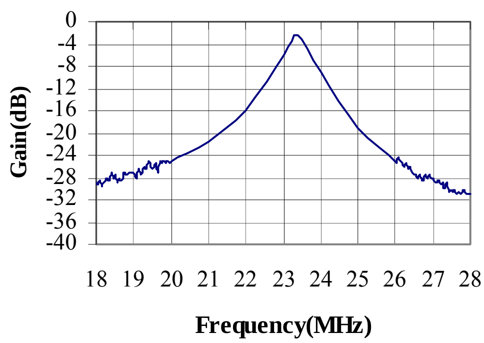

Fig. 3 Frequency response of single two comb resonators

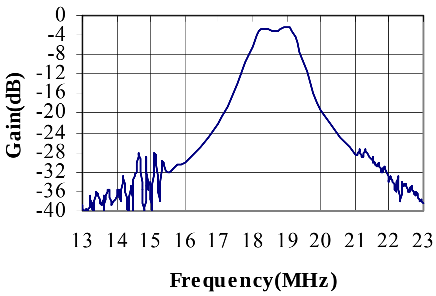

Fig. 4 Frequency response of series two-resonator microelectromechanical filter

10. Conclusion

A GA-tuned microelectromechanical MEMS filter was presented in this work. A digital bandpass filter was considered and the parameters were tuned using GA. After tuning, the parameters were related with the equivalent microelectromechanical model and the geometry of the filter was determined. Simulation results show that the frequency response of the designed filter is good and matches well with the desired response. The proposed series MEMS filters can be used in areas like mobile communication and satellite systems and requires areas of less than 0.005 mm2 per device on an average. Future direction of research can be directed towards optimizing (other than the geometrical properties of filter), the frequency-dependent loss mechanisms, electromechanical coupling and matching tolerances, which can also affect the ultimate performance and the maximum operating frequency range of the described filters.

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APPENDIX-I (Derivation of equation (1))

Consider the 1st and 2nd order mechanical resonators shown in figure A.1.

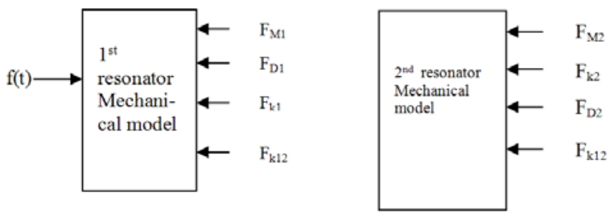

Fig. A.1 Forces acting on 1st and 2nd resonator Model.

By Newton's second law

$$F_{M1} + F_{D1} + F_{k1} + F_{k12} = f(t) \qquad \text{-----(A.1)}$$

$$M_1(d^2x_1/dt^2) + D_1 (dx_1/dt) + k_1x_1 + k_{12}[x_1 - x_2] = f(t)$$

The S-domain equivalent representation is given by

$$M_1s^2X_1(s) + D_1sX_1(s) + k_1 X_1(s) + k_{12}[X_1(s) - X_2(s)] = F(s)$$

$$X_1(s)[M_1s^2 + D_1s + k_1 + k_{12}] - k_{12}[X_2(s)] = F(s) \qquad \text{----(A.2)}$$

Similarly for the 2nd resonator model

$$FM_2 + F_{k2} + F_{D2} + F_{k12} = 0 \qquad \text{----- (A.3)}$$

$$M_2 (d^2x_2/dt^2) + D_2 (dx_2/dt) + k_2 x_2 + k_{12} [x_2 - x_1] = 0$$

$$M_2 s^2 X_2(s) + D_2 s X_2(s) + k_2 X_2(s) + k_{12} [X_2(s) - X_1(s)] = 0$$

$$X_2(s)[M_2s^2 + D_2s + k_2 + k_{12}] = k_{12} [X1(s)] \qquad \text{-----(A.4)}$$

From equations (A.1) to (A.4), equation (1) can be obtained.

APPENDIX-II (Derivation of equation (2))

From the theory of parallel capacitor for a fixed voltage applied across the plates with variable distance,

$$I = \partial(CV)/\partial x + \partial(CV)/\partial t$$

Since C = f(x) alone and V is a constant = Vpo = (d.c. bias at the output port). Using this,
Io = Vpo $(\partial(C)/\partial x)o$
Similarly,
Ix = Vpi $(\partial(C)/\partial x)i = 1/\alpha$ **w**here V_{pi} = dc bias at the input port **&** α =Transformation parameter
Therefore,
Amplification factor $(\phi_i) = I_0 / I_x = Vpo (\partial C/\partial x)_o / Vpi (\partial C/\partial x)_i$
The transfer function relating I_0 & V_i is obtained as

$$I_0 / V_i = \frac{j\omega Vpo\ Vpi\ (\partial C/\partial x)_i (\partial C/\partial x)_o}{G_{2n} (j\omega)^{2n} + G_{2n-1} (j\omega)^{2n-1} + G_{2n-2} (j\omega)^{2n-2} \ldots\ldots + G_0}$$

M1 Kn Dn Ln Cn Rn Ix
where G_{2n} and G_{2n-1} ……G_0 are constants and are functions of the filter geometry.

APPENDIX-III

The microelectromechanical filter transfer function is given as,

$$H(Z) = \frac{(Z+1)^2}{\{(Z^2(M_1+D_1+k_1))+(Z(-2M_1+2k_1))+(M_1+k_1-D_1)\}}$$

Comparing the microelectromechanical filter with generalized form of the digital filter,
$K = 1/(M_1+D_1+k_1)$; $a_1 = (2M_1+2k_1) / (M_1+D_1+k_1)$ and $a_2 = (M_1-D_1+k_1) / (M_1+D_1+k_1)$