Modeling and Simulation of MEMS-Based Comb Drive Actuator for Development of Single Axis Gyroscope, Using Bond Graph

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Abstract-A comb drive is an important component of MEMS-based actuators used in many applications such as a dispenser and a fluidic pump, and as a sensor in an accelerometer and in MEMS gyroscope. These energy systems, generally called mechatronic systems, are coupled multi-domain. Modeling and simulation of mechatronic systems is a challenging task. For coupled multidomain energy systems recently Bond Graph Method (BGM) has emerged as a method of choice. The system is seen as an interplay of power and energy variables, thus introducing the immortal concept of cause and effect. The two primary forces, electromechanical and electrostatic, are cast into the cause and effect paradigm whilst expressing power into effort and flow variables.

In this research work the main focus is on the investigation of the control parameters of laterally vibrating electrostatic comb-drive actuators. 20-SIM, a commercial bond graph package, is used to investigate the influence of control parameters on performance of the comb drive. The design process of system-on-chip (SoC) MEMS can be improved by this type of analysis. The comb-drive is represented here as a main source of actuation which is vibration in lateral direction. The work can be used as any design application as a cooling system for microprocessors used in space vehicles or a drug delivery system based on fluidic pump in on-a-chip systems. The multi-physics system of a robust comb-drive is modeled and solved using the 20-SIM, a commercial bond graph software. In this model, the driving voltage is taken into account. The comb drive displacement and electrostatic force are in direct relation to the square of the driving voltage. In this method, a model based on BGM is developed and then directly simulated using 20-SIM (a commercial software of Bond Graph modeling). Since bond graph is a precise mathematical model, the **state**-space equations of physical dynamic system can be solved. The bond graph simulations lead to the desired state space equations, which unfold the dynamic response of the physical system.

Keywords-Comb Drive, Gyroscope, MEMS, Modeling and Simulation, Bond Graph Method

I. INTRODUCTION

The drive for miniaturization propelled technology towards smaller devices. Micro Electro Mechanical Systems (MEMS) or the more European term Micro Systems Technology (MST), are devices whose applications are being discovered.

The comb-drive actuator is a basic building block of MEMS. Comb drive basically works on the generation of the electrostatic between the integrated conducting fingers moves relatively. As it is capable of generating the force, it has numerous applications in micro-mechanical systems. As an actuator MEMS Micro-gripper [I], probe based scanning devices [ii], on chip MEMS seismic accelerometers [iii], bi-directional rotation in MEMS actuators [iv], laterally oscillating gyroscopes [v] and RF filters [vi]. Therefore, improvements in comb drive actuators will have lasting effects in MEMS.

Particularly, in electrostatic actuator our interest is always in comb finger designs. These designs would generate more deflection profiles with the change of electrostatic force with linear shapes. These linear relationships, due to the action of a linear suspension spring, Reference [vii] will partially compensate for the mechanical restoring force. The drive voltage of these electrostatic actuators can be lowered by the electrostatic force of the spring. Moreover, this force may cause a change in resonant frequency.

In some researches people have investigated different comb shapes. Scheme [vii] reported fabrication methods for fingers, which are sensitive to small amount of displacements and drastically reduces the separation gap. These fingers were design supports maximum possible force output which is needed to minimize the voltage requirements at a nearly constant rate. The search of high-force actuators continued in the work of Scheme [viii].

The synthesis process demands efficient tools to enable designing of complex MEMS. This involves physical interchangeability with robustness between different domain of energy like electrostatic, mechanical, thermal optical, fluidic and magnetic energies. Several groups are working on this and reported the deficiency in different MEMS design tools, including CAEMEMS [ix] (Univ. of Michigan). (Microcosm/ M.I.T.), IntelliCAD [x] (IntelliSense Corp.), MEMCAD [xi]. These design tools focus on two perspectives:

i) numerical simulation processes of self-consistent electromechanical integrated comb drive,
ii) 3D modeling of layout.

Now the product life cycle of MEMS is made cumbersome by the modeling and simulation using these software, and FEM packages, such as ANSYS. This research work is aimed provide an ease to MEMS design and to cut down the length of the whole effort by employing the power of Bond Graph Method. The multiphysics approach and cross-domain reach of bond graph method enables us to use the coupled domains and work under the supposition that the domains have decoupled under some assumed approximations. Such approxima-tions have usually made the model to deviate from real system specifications as it is not considering the unexpected behavior of physical conditions and fabrication limitations. It is expected that theoretically the Bond Graph approach shall bring the model closer to empirical results as all physical conditions can be incorporated in it. Though the methodology has been in use since the last three decades, its power has been fully realized recently, while its object oriented modeling capabilities and merging of genetic programming has been exploited to the greatest benefit.

Bond graph method has been applied to RF MEMS comb drive switches by Rosenberg et al [xii]. The same was tried on vertical comb drive actuator in this paper. The initial effort has been focused on formulating the bond graph while tuning it to have a system approach of the model available for further results to be extracted by specifying the various parameters in the state space of the bond graph method.

II. PHYSICAL AND MATHEMATICAL MODEL

Developing a bond graph model and thus state space of a comb drive actuator with capability of continuous motion and large static displacement has always been the main focus of research in micro domain.

The actuators consist of two inter-digitized fingers, with one connected to a suspension and the other is fixed. The actuator is designed to be stiff in the orthogonal direction and only respond in the displacement direction [xiii]. The electrostatic forces, generated by applied voltage, cause deflection of the movable comb and vary directly with the square of the applied voltage.

Different comb designs, investigated for variations in displacement due to electrostatic driving forces generated by the applied voltage, have already been modeled by a robust finite element method and commercial multi-physics FEM package ANSYS [xvi].

The authors in this paper introduce the implementation of BGM by constructing a Bond graph model to get the variation of electrostatic force and displacement of comb drive with voltage. The model acquired is directly solved and simulated on 20-SIM, commercially available BGM software. BGM provides an easy way to investigate the system behavior with the variation of different parameters directly, without changing the basic design of system. It is a special ability of BGM which enhances the robustness of parametric study of multi physics system with reliability and repeatability.

The electrostatic Comb-drive actuator performance relies on its electrostatic characteristics [xiii]. In Fig. 1 voltage difference is applied between the two fingers, keeping the moving finger at ground potential; thus, a potential difference causes the fingers (electrodes) to be electrically charged. This results in an induced capacitance in the two electrodes. The electrostatic force displaces the movable finger in x direction. The driving force F can be expressed as:

$$F = \partial U / \partial g = nt\varepsilon_o\varepsilon_r V^2 / 2g \qquad (1)$$

here
U = Energy related to applied potential V,
ε_o = Permittivity in the free space, equal to 8.85 pF/m,
ε_r = Relative permittivity of the dielectric material between the two electrodes
n = Number of the electrode pairs,
t = Electrode thickness and
g = Gap between two fingers.
Considering an elastic displacement in the movable finger, according to Hooke's Law:

$$Fs = K_x x \qquad (2)$$

x is the displacement of the movable finger and K_x is the stiffness in x direction. Scheme [xv] and Scheme [xvi] has showed in their work to derive the stiffness of the spring. In equilibrium, the two forces Fs and F are equal, in this case x is a function of the driving potential (V), thickness of comb (t), the gap (g), the stiffness (K_x) and the number of electrodes (n) as:

$$x = nt\varepsilon_o\varepsilon_r V^2 / 2K_x g \qquad (3)$$

Equation 3 shows that the actuator displacement deviates from the linear behavior (increase in applied voltage causes an increase in displacement) and follows the voltage-stroke relation for the Combo-drive.

II. MODELLING THE SYSTEM THROUGH BOND GRAPH METHOD

The Modeling of a MEMS device carries with it certain inherent problems, which have lead to a method of formulation that does not always yield the most practical results. The designer has to bank upon numerous assumptions. The numbers of assumption widen the chasm between ideal and real system. The factors distancing the ideal or assumed system from the real system are:

1) Multi-domain system where the power flows from electrical to mechanical domains due to the capacitance variation (piezoelectric effect) which results in the Carioles Forces in the comb drive.
2) The relationship of various parameters is non-linear.

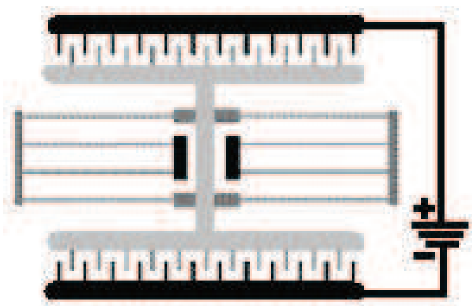

Fig. 1. The original actuator with folded-flexure suspension. This is a traditional actuator design with symmetry about x- and y-axis. [xvii]

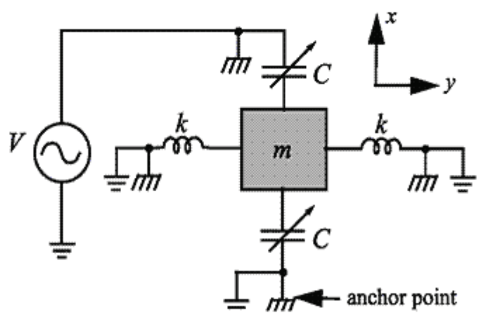

Fig. 2. A Mixed domain structure view of comb drive with a voltage source. [xiii]

3) A single model of a comb finger with the flexure alley has to be extended to the whole comb drive (with an average of 20 fingers). This requires an ability to generate algebraic loops, thus enabling the use of advanced techniques such as Genetic Algorithm [xii].

The authors linearized the system and used some approximations to unfold domain information; these approximations enable the system to give empirical results through BGM.

BGM is based on ancient "cause-effect" theory and provides the domain independences in multi-domain system modeling. Four system variables are to be defined for any domain. To implement BGM on multidomain system firstly the identification of two power variables for that domain are needed. Some examples of power variables of system are shown in Table I. These variables are selected in such a manner that the product of these variables is always equal to the "power" in that domain. These variables are the effort and flow of that specific domain. After identifying these variables, the causality assignment come i.e., the classification of these elements into cause and effect in the system. The other two variables are called co-energy variables. As energy is the integral of power so these two variables are the integrals of effort and flow variables. The co-energy variables help to understand the energy flow of the system.

These elements consist of two energy sources, the source of flow (Sf) and source of effort (Se). Three energy elements, first for kinetic energy storage, i.e. inductor (I), second for potential energy storage, i.e. capacitor (C) and the third for system energy dissipation i.e. resistor (R).

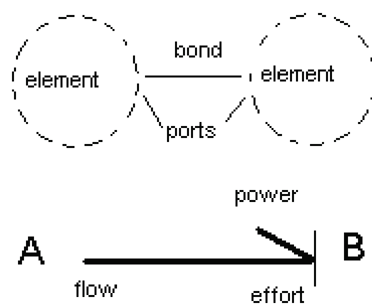

Fig. 3. Ports and bonds of Bond Graph

To interplay between different domains and incorporate the causality change between variables, two convertors are used i.e. Transformer (TF) and Gyrator (GY). These two convertors use to incorporate the change of domain, like Electrical to mechanical in our system, and to step up and down the power variables, like transformer in electrical system. Last two are the junctions, i.e. 0 and 1 junctions, use to define the parallel and series combination of the elements. With the help of these nine elements one can model the universe as it is a complete unified modeling technique. The system of every domain like electrical, mechanical, mechanical rotation, hydraulic and thermal or combination of any of these can be built by taking appropriate domain variable as detailed in Table (I) and the system elements.

These nine elements are connected with each other through the ports Fig. 3. These ports contain the information of causal and the energy flow directions of the system.

The connections of elements through ports having causal and energy information in accordance with the precise physics of the system, give a complete augmented Bond Graph of the system. Unlike the traditional modeling techniques BGM defines the system flow and unfold the mathematics of the system through the physical information incorporated in model.

TABLE I
VARIABLES OF DIFFERENT DOMAIN IN BOND GRAPH METHOD.

Domain	Variables of Effort	Variables of Flow
Mechanical	Force (F)	Velocity (v)
	Torque (τ)	Angular Velocity (ω)
Electrical	Potential Diff. (V)	Electric Current (I)
Hydraulic	Hydraulic Pressure (P)	Volume flow rate (dQ/dt)
Thermal	Thermodynamic Temperature(T)	Rate of Entropy change (ds/dt)
	Pressure (P)	Volume change rate (dV/dt)
Chemical	Chemical potential (μ)	Mole flow rate (dN/dt)
	Enthalpy (h)	Mass flow rate (dm/dt)
Magnetic	Magnetomotive force (e_m)	Magnetic flux (φ)

Our comb drive is based on electrical and mechanical domains. The interconnectivity of mechanical and electrical domain variables Fig. 4 for the comb drive system has been developed according to the physics of the system and rules of BGM.

The Bond Graph of a physical system is developed by identification of domain specific system elements and connecting them according to the power flow pattern and causality assignments. This Bond Graph will have the sufficient information of the system energy flows and it precisely unfolds the mathematical model i.e. direct facilitation in the dynamic response of the physical system. Now by assigning the value to elements of bond graph model, according to physical system, the simulations are being done on the commercial Bond Graph software, 20-SIM.

Our developed bond graph model Fig. 4 for a comb drive actuator is derived from a physical design of a traditional x and y-axis symmetric comb drive Fig.1 [xvii]. A mixed domain structure of that system with voltage source, V, is shown in Fig. 2 [xiii]. It consists of a mass suspended by two folded beams flexures, thus constituting a mass spring damper system. This derived model is then simulated and trend of results, for different values of parameters, have been compared with the results of FEM [xiv].

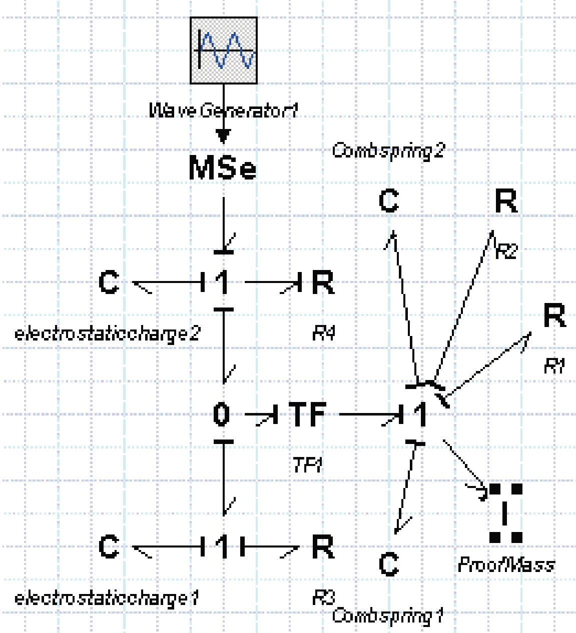

Fig. 4. Bond Graph Model of electrostatic comb-drive.

III. Results and Discussion

The variation in comb displacement and electrostatic force in the comb spring against the applied voltage is studied. Eq. (1) and (3) show that the displacement of combs and the force generated is directly proportional to the square of applied voltage. The authors have developed bond graph model of the system Fig. 4 with the help of physical model only, and simulated the Bond Graph Model on 20-SIM. Fig. 5 shows the relationship of applied voltage, against displacement and electrostatic force. This relationship of physical model exactly follows the trend represented in mathematical Eq. (1) and (3).

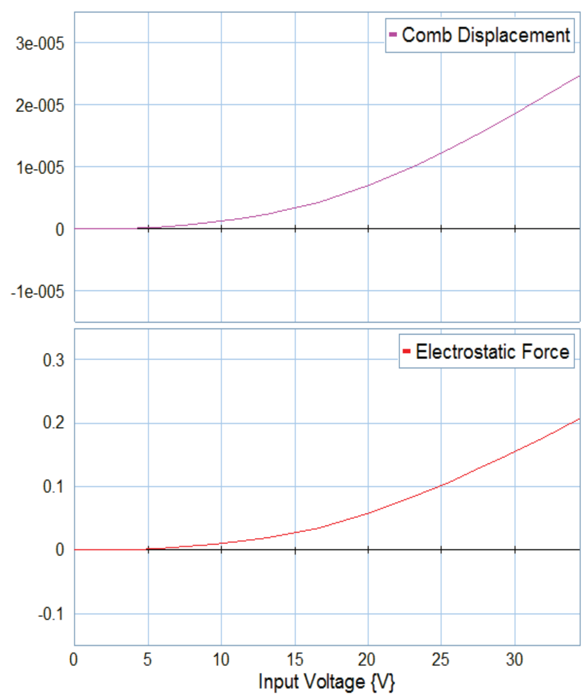

Fig. 5. Simulation of Comb Drive displacement and electrostatic force against driving voltage at initial parameters.

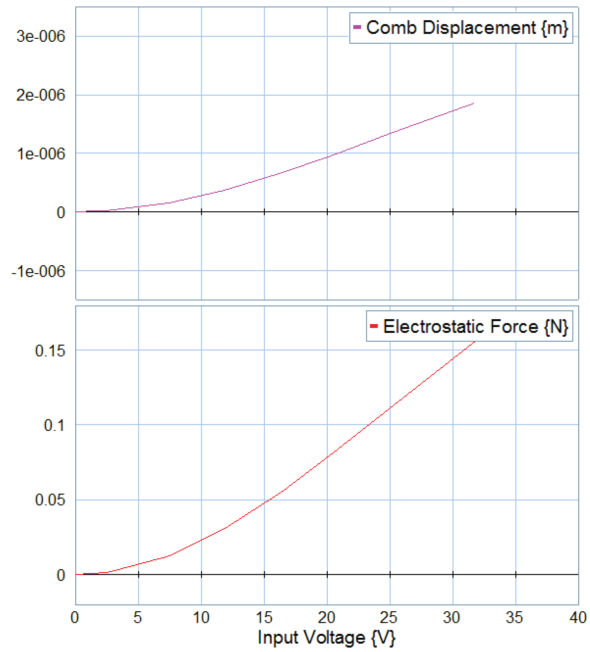

Fig. 6. Current Frequency doubled from initial value.

In the current study, the Bond Graph Method is applied to check the effects of Comb's design parameters on the actuation performance Figs. 1-9. Fig. 5 shows the variation of the Comb displacement and generated electrostatic force with the driving voltage of 40 volts. Figure shows that electrostatic force and displacement is linearly related to voltage squared with constant spring stiffness and other parameters.

The initial parameters of the system are taken as :

MSe	= Input Voltage	= 40V
f	= Current frequency	= 50rps
R3	= Elec. Resistance	= 0.05ohm
R4	= Elec. Resistance	= 0.05ohm
C	= Charge on fingered cap. 1	= 1.456exp-8C
C	= Charge on fingered cap. 2	= 1.456exp-8C
R1	= Mech Damping	= 0.00323Ns/m
R2	= Mech Damping	= 0.00323Ns/m
C	= Comb Spring Stiffness1	= 83333N/m
C	= Comb Spring Stiffness2	= 83333N/m
I	= proof mass	= 0.5g

The natural frequency for the free undamped vibration of a uniform cantilever affects the displacement and is a function of its length, cross-section, and boundary conditions. Fig. 6 shows the effect of doubling thr frequency of current on the electrostatic force and comb displacement observed in comb-drive. This dependence of displacement and force on natural frequency has been simulated at 40V and the results are displayed which shows that the displacement of the system decreases with the increase in current frequency, as expected.

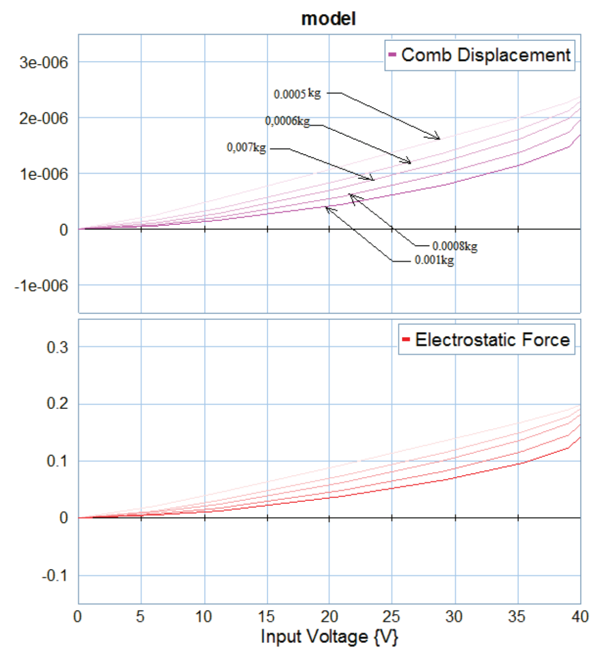

Fig. 7. Increasing Proof Mass giving decrease in Comb displacement and force

The results shown in Fig. 7 indicate that for a driving voltage of 40 volts, as the value of proof mass is increased from 0.0005 to 0.001kg, the inertia of the drive increased and so is the Comb displacement decreased. This effect of the Comb is also expected.

The displacement variation rate is shown to decrease with the decrease of the proof mass (m) as well. This effect verifies the above result.

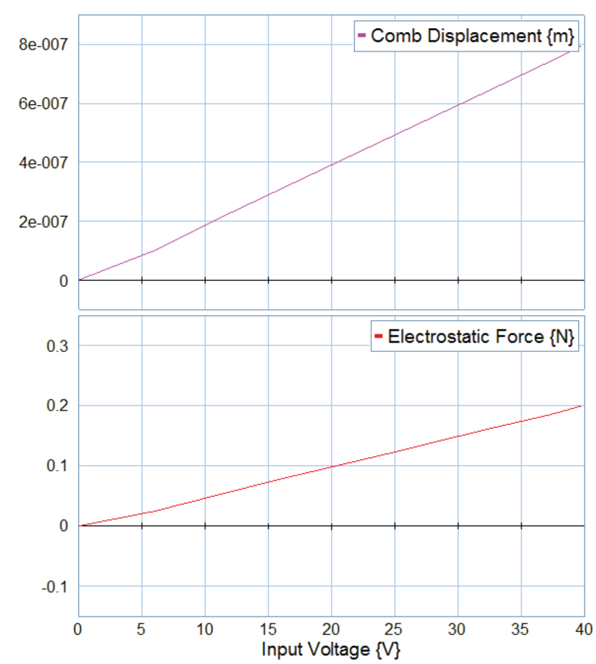

Fig. 8. Stiffness increased by three times

If the value of stiffness is increased from 83333 to 250000, the comb displacement decreases. Fig. 8 concurs with the relation between stiffness and Comb displacement for 40V driving voltage; other parameters are same as in Fig. 5.

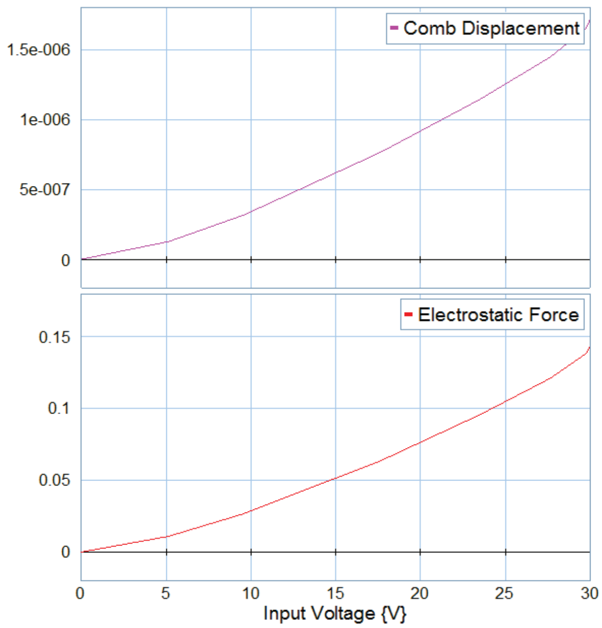

Fig. 9. 30V

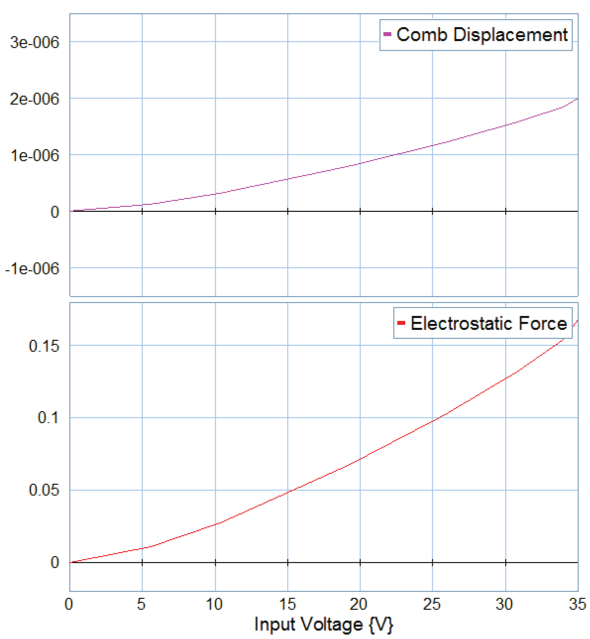

Fig. 10. 35V

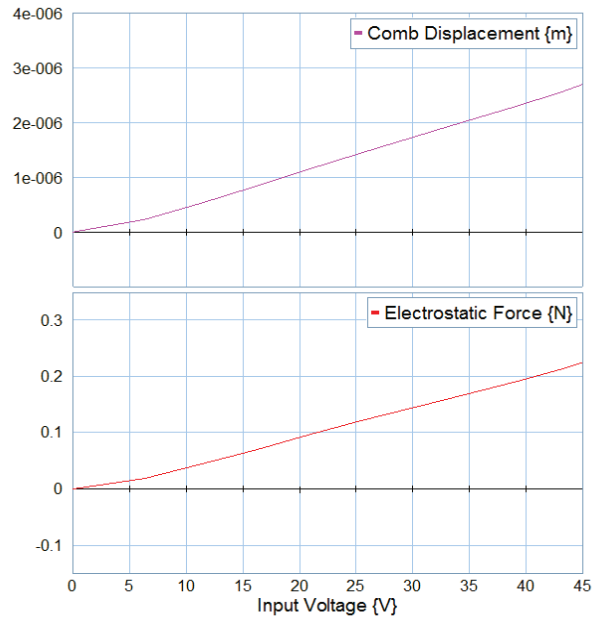

Fig. 11. 45V

When supplied voltage is decreased as in Fig. 9-12, the displacement of the comb drive will also decrease. In case if we increase the supplied voltage, an increase in the comb resistance is observed for the taken comb design, as shown in Fig. 11 and 12. In these figures, variation rate in the displacement of comb drive is changed with supplied voltage.

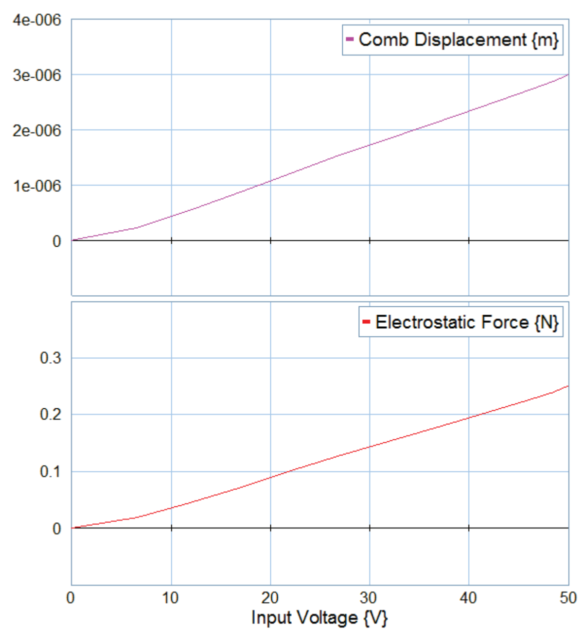

Fig. 12. 50V

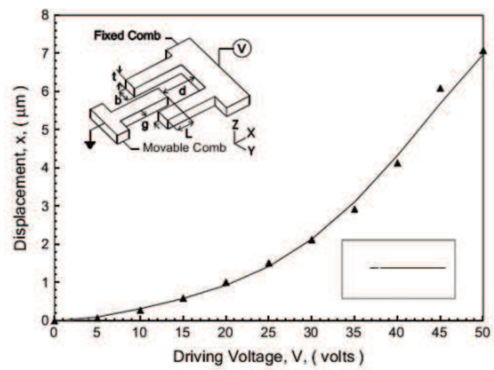

Fig. 13. Graph indicating variation of displacement versus the applied voltage, (V) of Comb-drive. [xiv]

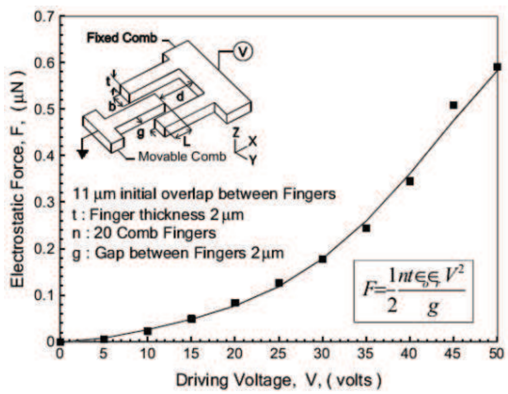

Fig. 14. Graph indicating variation of electrostatic force and applied voltage [xiv].

In order to utilize the current study results in the design optimization of comb drives with linear nature, we have made an effort to condense these results into non-dimensional compact form that correlates the studied geometric parameters of the modeled comb-drive with its displacement. Utilizing Newton Raphson Method, built-in with 20-SIM, it is observed that the displacement values in Fig. 6-10 are effectively represented by Eq. (1) and (3) and results of FE and Mixed domain method presented in [xiv] also confirms the trends of these simulations.

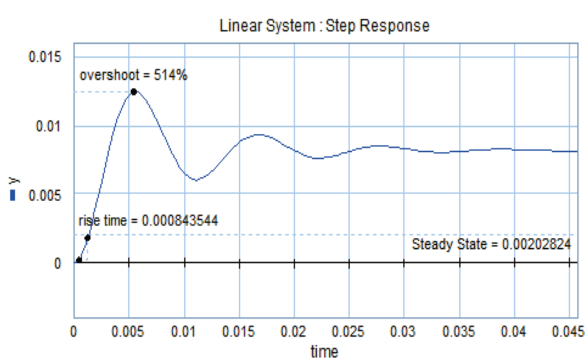

Fig. 15. Step Response Plot

The step response of the system is extracted, Fig. 15 and its shown that the settling time of the system is found 0.05 sec.

With sinusoidal input it is observed the system oscillated sinusoidally in response time of 0.05sec.

The simulation through the bond graph model is studied with the variation of different parameters and it is evident that the system design parameter are successfully studied and altered through this method and system followed all the expected trends.

IV. CONCLUSION

In this work, Bond Graph Analysis is used to explore the effect of the design parameter of laterally actuated electrostatic comb drive on the actuation performance. The comb displacement induced and the generated electrostatic force in comb are directly proportional to the square of driving voltage. The bond graph method is successfully applied to the MEMS system to study the variations of considered variables with the change of parameters. The variation follows the expected trends of comb drive actuation. Now from these results, by considering the actual parameters of comb drive, an optimized design of this kind of a system can be developed without indulging in an extensive mathematical modeling. Bond graph method basically depends on correct physical model of the system and supports to develop the mathematical equations of the physical system itself. Assumptions discussed earlier can be tackled by taking suitable values of system variables and improving the system performance by inserting the values of parameters ignored in this model.

The effect of comb-drive design parameters on actuation performance is explored. Eq. (1) and (3) shows that the displacement of combs and the force generated is directly proportional to the square of applied voltage. The same results are indicated by the results of FEM and PolyPUMP. The relationship of our developed physical model follows the trend represented in these results.

In this research, the coupled electrostatic and mechanical analysis of MEMS Comb-Drive has been performed. Mechanical Analysis done through Finite Element Method (FEM) and Electrostatic Analysis is done by the Boundary Element Method. Several design parameters of comb drive like overlap of the fingers, folded flexure spring length which effect the stiffness and the voltage applied to the comb fingers were addressed and their effects were studied on different variables like mass, system's natural frequency and comb displacement, using ANSYS by [xiv]. Simulations on 20-SIM through bond graph method are following the same trends and generating the same effects as ANSYS results.

V. RECOMMENDATIONS

An optimized comb drive based gyroscope is to be designed with Bond Graph Method, in which the gyroscope's design issues and problems can be simulated, studied, optimized and verified.

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