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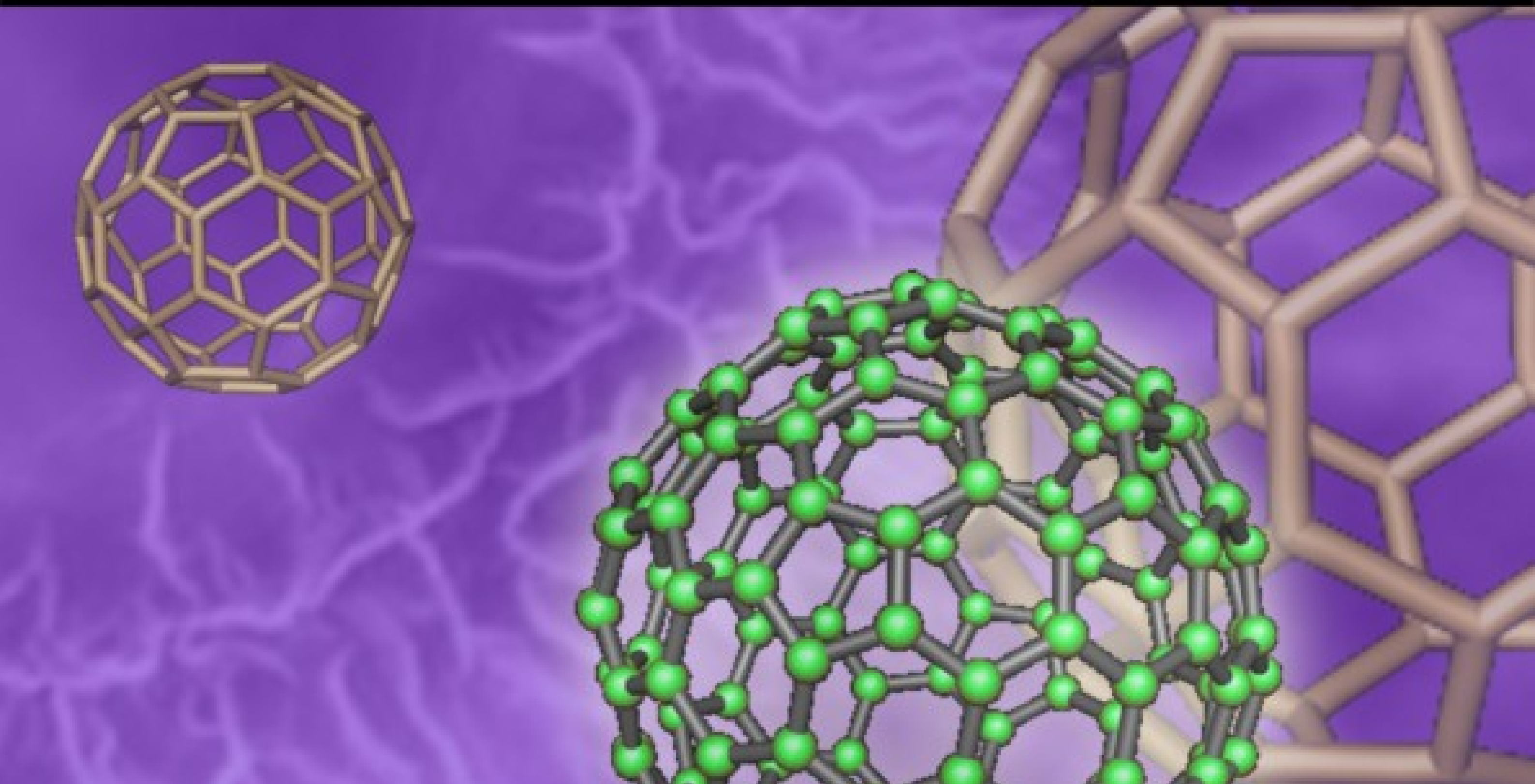

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Wireless Sensor Network: Modeling and Analysis of MEMS based Nano-Nodes

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Abstract: We have analyzed the implications of innovations in MEMS on Wireless Sensor Networks (WSN) and have modeled MEMS elements from a device prospective. We have commented on the advantages as well as the challenges that exist in this technology and described the important factors that need to be kept under consideration for the calculation of the reliability for practical implementation of MEMS based devices and the scope of modeling. We have executed the work on SUGAR of MATLAB; the proposal is then compared to the recent developments taking place and with the other experimental result which are reported. Thus a comprehensive modeling aspect of MEMS based elements of a WSN is shown. Modeling of tunable comb resonators, Vertically-shaped comb-resonators and thermal actuator has been shown and the implication of modeling in such devices has been shown. Various computations were implemented and results being given supporting the data from the experiments in recent years. *Copyright © 2009 IFSA.*

Keywords: Wireless sensor networks, Nanotechnology, MEMS, Sensor nodes, Reliability

1. Introduction

Nanotechnology uses the smallest unit of matter to engineer new materials and devices atom by atom, aiming at achieving superior properties and performance through atomic scale architecture. The combination of recent technological advances in electronics, nanotechnology, wireless communications, computing, and networking has hastened the development of Wireless Sensor Networks (WSNs) technology. Wireless Sensor and Actor Networks (WSANs) constitute an emerging and pervasive technology that is attracting increased interest for a wide range of applications. WSN see application in various areas like space research, biomedical engineering, military applications such as battlefield surveillance and the quest for making low power, reliable and cheap sensor nodes has been a prime focus in recent years.

Recent developments in MEMS and wireless technology together enable remote sensing of the environment using a large number of miniaturized wireless sensor nodes [1]. A wireless sensor node typically consists of three major subsystems: Computation, Communication and Sensing where MEMS devices are extensively used in the sensing portion to sense various parameters as reliant on the need of the system. In our previous work we have shown Nano based WSN where the importance of CNT and MEMS technology in WSN is shown [2].

A sensor node AccuMicroMotion based on MEMS is proposed in [3] that has the ability to detect motion in six degrees of freedom for the application of physiological activity monitoring. MEMS based sensors used in WSN for environmental monitoring, traffic monitoring and water quality monitoring can be used for prevention of undesirable events has been shown in [4]. Battery less-Wireless MEMS Sensor System with 3D Loop Antenna RFID based device has been proposed by Sasaki which can be used for passive RFID based sensors [8]. MEMS based sensors networks utilization for space application has been shown by Erfy in [7]. MEMS capacitive sensor for chemical detection has been put forth in [5]. Thus we can see that MEMS devices playing an important role in Sensors and giving many advantages over their traditional counterparts. Reliability and failure mechanism in MEMS, its implications for WSN and the changes that are needed to be made in the modeling of the nodal software and operating system have been the major challenges in MEMS based WSNs. We have implemented modeling solutions of [7, 8] in our work earlier [35].

2. MEMS Sensors

Trends toward smaller size, higher performance, and greater functionality for electronic devices are made possible by the success of solid-state microelectronics technology. In the late 1980s, the silicon Very-Large-Scale-Integrated (VLSI) design and manufacturing was developed for use in field of Micro-Electro-Mechanical System (MEMS). This field is called by a wide variety of names in different parts of the world: micro-electromechanical systems (MEMS), micro-system technology (MST), micromechanics, and micro total analysis systems (μ-TAS) etc. These systems interface with both electronic and non-electronic signals and interact with non-electrical physical world as well as the electronic world by merging signal processing with sensing and/or actuation. Instead of dealing with electrical signals, MEMS also deals with moving-part mechanical elements, making miniature systems possible such as accelerometers, fluid-pressure and flow sensors, gyroscopes, and micro-optical devices. We know that Nanotechnology has enabled realization of low power devices such as MEMS devices and CNT based FETs which can be a part of Nano WSN as shown in details in [12]. An improvement in techniques of Nano-characterization and Nano-fabrication has helped us to pave the way to develop many novel materials that can be applied to various spheres of technology. For example the impact of Nanotechnology on Wireless Communications has been shown by Er. Ping Li in [14]. An Architecture of Quantum-Based Nano-sensor Node for Future Wireless Sensor Networks has been proposed [10]. WSN in space application has been shown in [6] which use adaptive MEMS antennas. Wireless Sensor Networks with Biomedical Applications has been shown by Zachary Walker describing the importance of Middleware [22]. Miniature Acoustic Communication Subsystem Architecture for Underwater Wireless Sensor Networks has been proposed by Saunvit Pandya [25]. WSN architecture for the Wireless Health Mobile Bio-diagnostic System for physiological studies has been proposed [13]. Thus, we have expanded and proposed designing and modeling of MEMS based array of sensors in our paper that can lead to its practical applications in these areas.

3. Sugar Modeling of MEMS Elements of a WSN System

During the last two decades, the field of micro electro-mechanical systems (MEMS) has advanced from producing simple-function devices to building systems of greater complexity. This has led to the development and widespread use of computer-aided engineering (CAE) tools for MEMS. Although these tools have been successful in simulating the behavior of simple-function devices, they have not been as successful in simulating the behavior of more complex systems on a personal computer (PC) nor within a practical timeframe. In essence, depending on how well the CAE software facilitates the design process, reduces the time of computation, and agrees with realistic outcomes, the software can be an invaluable aid for technological advancements in MEMS. With the ultimate goal of quickly and accurately simulating complex systems, we present efficient methods to configure, model, and simulate MEMS that are composed of a large number of lumped components. These methods are packaged in a CAE for MEMS tool called SUGAR [26].

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Thus we can calculate various parameters required in reliability calculations from SUGAR simulation program as shown above. In this part we have implemented the modeling of the some of the MEMS based devices that have been recently proposed. As we know that these devices require very less energy and thus can be useful in active RFID and WSN systems and in some cases passive RFIDs too. The models can be added in to WSN as well as nano RFID, and since we are talking of MEMS manufacturing which is based on the lines of the VLSI we can very well integrate it with manufacturing of WSN elements which uses MEMS technology in the antenna manufacturing as shown earlier by us. The MEMS models we have modeled in this part have been recently proposed in 2008 February and were only made in laboratory with no real implementation. Modeling implemented by us will be helpful in true realization of these proposals. MEMS resonators have shown tremendous advantages for their application in real devices.

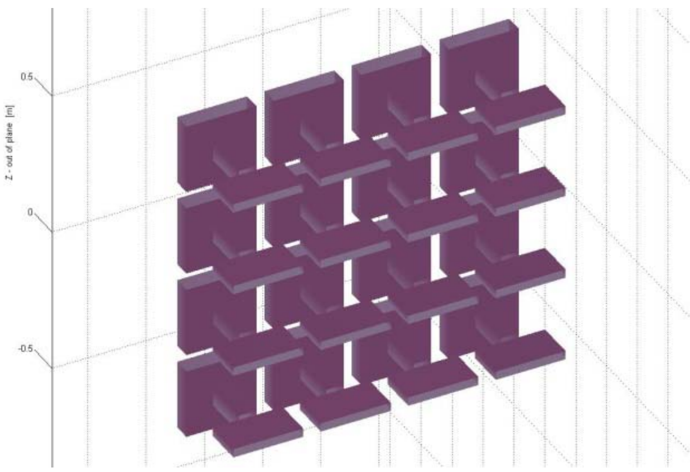


Fig. 1. Modeling of Array of cantilever MEMS sensors SUGAR- Diagram of Structure [22].

Code I
Array of Sensors

```
use("mumps.net")
use("stdlib.net")
gap=300u
gridDim=gap/3
fringeDim=40u
beamw = gridDim-fringeDim
beaml=200u
--Array junction
junction = { node{} }
for n=0,3 do --z
for m=0,3 do --y
--Nodes
junction[n] = node{0, m*gap, n*gap}
junction[n+1] = node{}
junction[n+2] = node{}
junction[n+3] = node{}
junction[n+4] = node{0, (m*gap), (n*gap)-(gap-beamw)/2}
--Beams
beam3d { junction[n], junction[n+1] ; material=p1, l=gap-beamw, w=gap-beamw, h=beamw, oy=90}
anchor { junction[n] ; material=p1, l=gap-beamw, w=gap-beamw, h=beamw, oy=90}
beam3d { junction[n+4], junction[n+2] ; material=p1, l=beaml, w=beamw, h=beamw, ox=90}
beam3d { junction[n+2], junction[n+3] ; material=p1, l=beaml/1.5, w=beamw/2, h=beamw*4, ox=90}
end
end
```

The development of tunable comb resonators that use vertically-shaped comb fingers as electrostatic springs has been shown in [32] which we have modeled in our work as shown below in Fig. 2.

We know that the force relationship in electrostatic comb- drive actuators

$$F = \frac{1}{2} V^2 \frac{\partial C}{\partial x} \approx \frac{N.\varepsilon_0.height}{gap} V^2 , \tag{1}$$

where V is the applied voltage, N is the number of comb-fingers. The equation is built upon some approximations but works fine.

Results from the model in MATLAB can be shown in the Fig. 2. Where force as a function of Voltage and height is given.

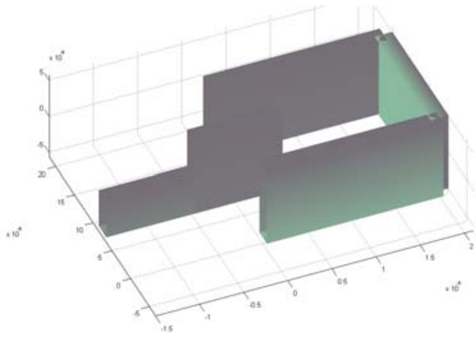
Modified tuned frequency for such devices can be realized as f_{tuned} where k_{mech} and k_{eff} are original and effective spring constants.

$$f_{tuned} = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m}} = \frac{1}{2\pi}\sqrt{\frac{k_{mech}+k_{elec}}{m}} \tag{2}$$

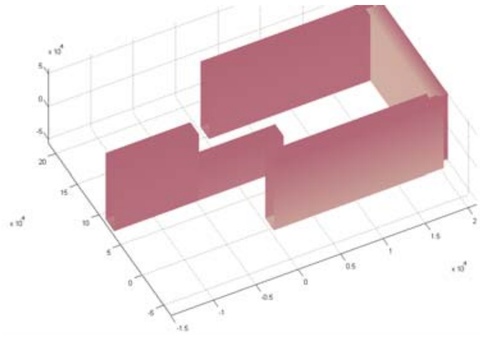
Also in terms of unturned resonant frequency it can be stated as

$$f_{tuned} = f_0\sqrt{1+\frac{k_{elec}}{k_{mech}}}, \quad (3)$$

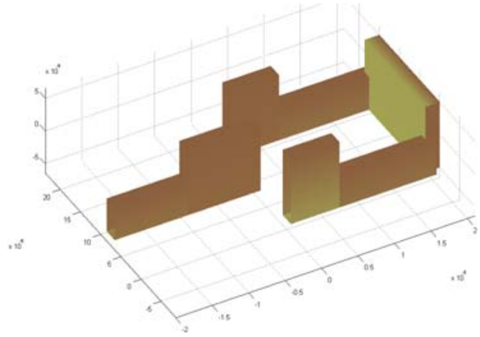
where f_0 is the unturned resonant frequency.



(a)



(b)



(c)

Fig. 2. Modeling of Vertically-Shaped Tunable MEMS Resonators has been shown with the variations in the figures above. Shown in (a) is a design models that creates a "weakening" electrostatic spring that leads to lower resonant frequencies. Shown in (b) and (c) are designs models that create "stiffening" electrostatic springs that lead to higher resonant frequencies.

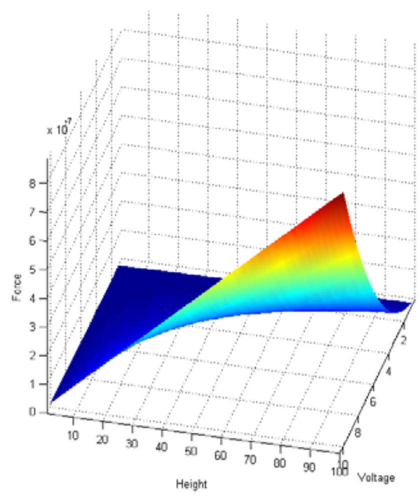


Fig. 3. Force as a function of Voltage and height in a tunable comb resonators as developed in the Library.

Vertically-shaped comb-resonators can create electrostatic springs without increasing the size of a single comb-pair is the main advantage of such systems that makes their modeling an important in their development. In our model we have clearly shown the moving finger as well as stationary finger.

A micro fabricated corona ionizer is developed for miniaturized air particle monitoring instruments was implemented in [33] which we have modeled. It is a negative corona-discharge-based micro fabricated ionizer that operates in atmospheric conditions. Model in Fig. 4 is built which is part of the work done to integrate all in a single platform in MATLAB. In the next model presentation, design and fabrication of a single-layer out-of-plane thermal actuator has been shown [34]. The step-bridge structure design enables bending and then buckling of the actuator in the out-of-plane direction by Joule heating, these models have been modeled and shown in the Fig. 5 and 6.

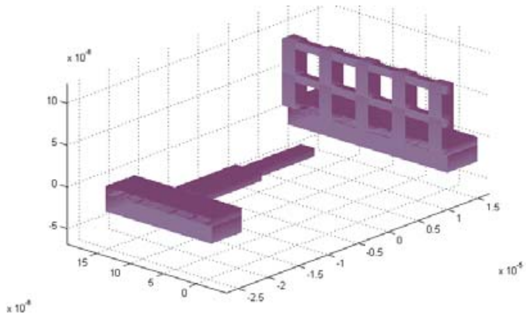


Fig. 4. Implementation of modeling aspect of a Micro fabricated Corona Ionizer has been shown in the above diagram.

The working was realized using prebuckling and post buckling deformations where prebuckling deformation amplitude U_{pre} of the actuator at the midpoint of the structure was expressed as [46].

$$U_{pre} = \frac{M_0 L^2}{8EI}\left(\frac{d}{L} - \left(\frac{d}{L}\right)^2\right)H_1, \tag{4}$$

where E and I are the young’s modulus and the moment of inertia and H1 is the function of h and the input power.

Results from the model in MATLAB can be shown in the graph where amplitude as a function of step height is given. (U_{pre}=f(d,L)), results being computed for the model clearly depicts the variations in amplitude can be studied more comprehensively as shown in the modeling.

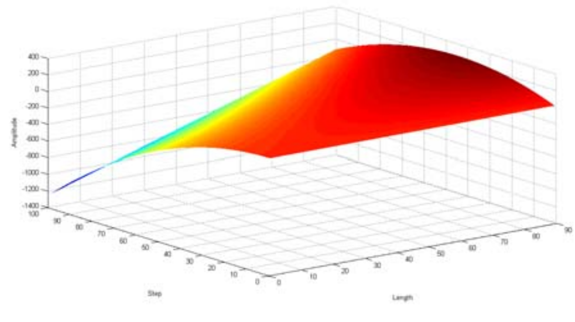


Fig. 5. Deformation amplitude as a function of step height and Length in the thermal actuator as developed in the library.

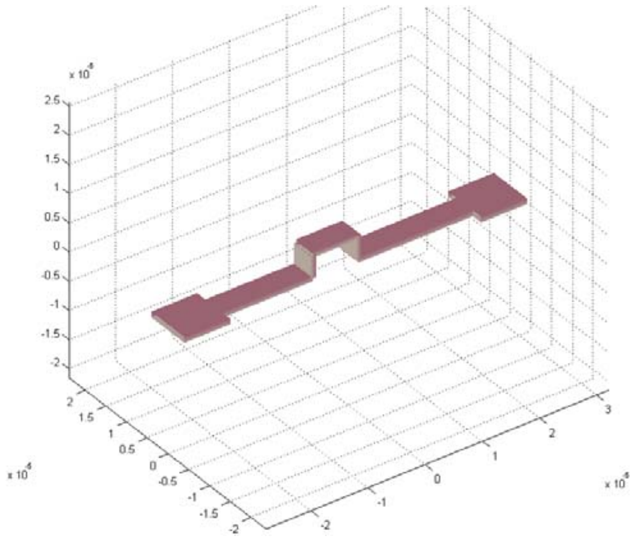


Fig. 6. A part of Single-Layer Step-Bridge Structure for Out-of-Plane Thermal Actuator has been modeled above.

From the buckle beam theory of eccentric axial load, the deflection of the step-bridge can be studied. As the length ratio d/L approaches to zero or one, the shape of the step-bridge is similar to the ideal clamped–clamped beam, and its buckling deformation becomes

$$U_{post} = \left(\frac{1}{\cos\left(\sqrt{\frac{P}{EI}} \frac{L}{2} \right)} - 1 \right) H_2, \tag{5}$$

where the parameter H_2 represents the influence of the step on U_{post}, and H_2 is also a function of h and the input power.

4. Reliability of WSN and Future Scope

Contemporary work in computation of WSN reliability is pretty generalized and Nano-scale devices based WSN has not been the sole focus of the research done in this area. In our previous work we have shown that MEMS reliability can be calculated using HPC thus making their practical applications possible [9]. Effects of the failure of sensor nodes are studied and no compromise data acquisition methods have been proposed in [21]. Requirement for sustained, reliable and fault-tolerant operations have been conferred and a solution has been proposed by Kaminska in [15].In this regard the reliability calculations by probabilistic graph models and algorithm have been demonstrated by Hosam M. F. AboElFotoh [17].

Reliability studies in respect to Common Cause Failures have been examined [20]. Modeling and evaluating the reliability of Wireless Sensor Networks as subject to common cause failure has been described in [18]. Data transport and the reliability of data transport protocols have been discussed in [19]. Thus if we can predict the cause of failure then we can modify the protocols in our system accordingly. In Nano domains the failure can be caused due to large number of problems and errors which needs to be modeled and predicted in advance. Ad hoc wireless architecture has been introduced by Kamiska in [15] for the sustainability of self-configuring Wireless Sensor Networks and the routing scheme forwards sensor data along fuzzy and intentionally redundant paths to provide for reliability and fault-tolerance has been proposed. In [23] Zhand Dingxing discusses coverage algorithm based on probability to evaluate point coverage. Reliability in Wireless Sensor Networks using Soft Sensing and Artificial Neural Network methodology has been demonstrated by Rubina Sultan [21]. Optimizing availability and reliability in Wireless Sensor Networks applications by the use of middle wares has been shown in [16]. Thus we need to develop middleware in accordance with the challenges that exist. Thus our model can be used for solving the current problem in reliability due to its high computation power and compatibility.

5. Discussion of some Abstraction Layer Properties and their Application in the Library Developed

Modeling of MEMS based sensor nodes plays the most important role in a WSN. Thus we can see that various elements have various properties which are defined on abstraction layer theories but to apply them in real applications modeling plays a very important role. MEMS antenna for RFID systems and their intricate modeling is an area that has been discussed earlier and many modeling solutions has been in implemented in recent years [35].

Inductance of straight line strip which is the most common type of MEMS Inductors used can be written as [24],

$$L = 2l\left[\ln\left(\frac{l}{\omega + t}\right) + 0.22\,\frac{\omega + t}{l} + 1.19\right], \tag{6}$$

where L is the segment inductance in nanohenries, l, w and t are the segment length, width and thickness, respectively, in centimeters. The strip inductors are good in the range of 0.5–4 nH. Higher inductances can be achieved using spiral inductors. The inductance of a single loop in nanohenries is given by

$$L = 4\pi a\left[\ln\left(\frac{8\pi a}{\omega}\right) - 2\right] \tag{7}$$

The operation parameters were described in [29], as measurements revealing the following failure modes of RF MEMS switches: stiction of the bridge of the devices under test due to charging, and breakdown of the dielectric. Low-frequency system to characterize the switching of capacitive RF MEMS switches that are normally operated and tested with GHz range signal frequency new equipment developed. Thus they are incorporated easily in the library being developed. Now a MEMS-Based Inductively Coupled RFID Transponder for Implantable Wireless Sensor Applications has been shown in [23]. And the formulae for induced voltage at the MEMS based transponder is, which of macro level given below.

$$v_T = \frac{\omega \cdot k \cdot \sqrt{L_T L_R} \cdot i_R}{\sqrt{\left(\frac{\omega L_T}{R_L} + \omega R_T C_T\right)^2 + \left(1 - \omega^2 L_T C_T + \frac{R_T}{R_L}\right)^2}}, \tag{8}$$

where ω is the working frequency in radian/s, k denotes the coupling coefficient between the two coils; L_T and L_R denote the transponder and reader coil inductance, respectively and i_R signifies the current flow in the reader coil. Here R_T is the resistance in series at working frequency for the transponder coil. R_L and C_T denote the load resistance and matching capacitance respectively, for building the parallel resonant circuit. Unifying these structures can be seen in MEMS based RFID systems. Thus the current can be calculated by dividing this V_T by resistance of the device.

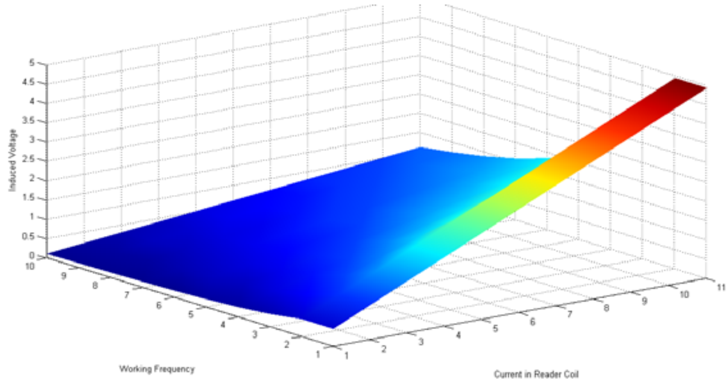


Fig. 7. Induced Voltage vs. working frequency vs. current in reader.

6. Conclusion

Thus we have shown how MEMS enabled devices can be used in a WSN environment and the challenges that need to be confronted with advantages of modeling. We have substantiated the integration of MEMS based devices in WSN. Modeling of tunable comb resonators, Vertically-shaped comb-resonators and thermal actuator has been shown and the implication of modeling in such devices has been elaborated. Future challenges exist in integration of MEMS modeling in the present domains like VHDL-AMS [27, 28] and they can provide complete solutions for MEMS based WSN nodes. The modeling of MEMS based nodes can be done in packages like MATLAB. Integration of Sugar [26] MEMS with reliability library as an added functionality with MATLAB also remains an area to work in this regard.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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