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Meshless Analysis of Radio Frequency Microelectromechanical Systems Shunt Switch

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ABSTRACT

Microelectromechanical systems (MEMS) have found applications in defence as well as in civilian sectors. Analysis of MEMS devices require complex 3-D meshes due to the presence of mechanical and electrostatic energy domains. On the other hand, meshless methods do not require the generation of mesh and perform the computational analysis by just sprinkling the points covering the domain. In this paper, meshless analysis of MEMS switches based on reproducing kernel particle method is reported. Numerical results for the static analysis of the switch are compared with the simulated results obtained using INTELLISUITE MEMS CAD tool.

Keywords: MEMS devices, meshless analysis methods, RF MEMS switches, shunt switches, RF MEMS technology, military communication, coplaner waveguide platform, reproducing kernel particle method, RKPM

1. INTRODUCTION

The microelectromechanical systems (MEMS) technology plays a key role in the miniaturisation of electronic modules and systems. Radio frequency microelectromechanical systems (RF MEMS) technology is an emerging sub-area of MEMS. The RF MEMS switches are the basic building-blocks for a variety of military and civilian communication applications[1]. These switches have demonstrated outstanding RF performance namely very low-insertion loss and high-isolation[2-4]. In addition, they operate at ultra-low power levels with excellent linearity and extremely low-signal distortion. The RF MEMS switches using metal membranes with capacitor coupling realised on a coplanar waveguide (CPW) platform combines the advantages of MEMS technology and that of coplanar wave-guide to achieve reduced size and better RF performance[5].

Development of fast, efficient and reliable CAD systems for the analysis of MEMS is more complicated than for traditional mechanical or electrical systems. It is essential to generate a volume mesh for a electromechanical micro device to perform the finite element based elastic analysis[6] and a surface mesh for the same micro device to perform exterior electrostatic analysis based on boundary element analysis[7,8]. Further, the volume mesh has to be compatible with the surface mesh. The complexity in mesh generation and in the selection of interpolation solution further increases, when more than one energy domain is involved.

An efficient approach to MEMS modelling and design is to consider mesh-less methods[9]. In these techniques, the numerical solution of partial differential equations are performed by sprinkling points covering the domain of interest. Mesh-less methods have several advantages over traditional mesh-based methods. The complicated mesh generation approach is replaced by simpler point-based approach, and for coupled domain analysis one does not worry about the compatibility of meshes. An overview and recent developments in meshless methods is reported by Belytschko[9], *et al*.

The first proposed meshless method was the smooth particle hydrodynamics technique for astrophysical applications[10-12]. Liu[13-18], *et al*. have shown that the smooth particle hydrodynamics approach does not satisfy the consistency conditions and can produce unstable results when applied to partial differential equations involving finite domains or boundaries. The consistency of smooth particle hydrodynamics technique can be established by introducing a correction function[13-18] and the new approach is referred to as the reproducing kernel particle method.

Other mesh-less methods developed includes the diffuse element method[19], element free Galerkin method[20-22], boundary node method[23], local boundary integral equations method[24-25], a mesh-less method based on the local symmetric weak form and the moving least squares approximation[26], finite-point method[27], cloud-based methods[28-29], and the partition of unity method[30]. In this paper reproducing kernel particle method is applied to analyse MEMS switch realised on a CPW platform.

2. MESHLESS ANALYSIS OF ELECTROMECHANICAL SYSTEMS

The major issue in a electromechanical system is to accurately predict the deflection or deformation of a micromechanical structure when subjected to electrostatic

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forces. In this paper, the deformation of RF MEMS switch realised on a CPW platform was obtained using the reproducing kernel particle method (RKPM). The governing equations, RKPM formulations, and numerical results are presented.

2.1 Governing Equations

The governing equation of a beam subjected to electrostatic forces[22] is given by:

$$\frac{\rho}{EI}\frac{\partial^2 u}{\partial t^2}+\frac{\partial^4 u}{\partial t^4}=-\frac{\tilde{w}}{2EIg^2}\left(1+0.65\frac{g}{\tilde{w}}\right) \tag{1}$$

where, ρ is the mass density per unit length of the beam, *u* is the displacement of the beam, *E* is the Young's modulus of the material, *I* is the moment of inertia, $\tilde{w}$ is the width of the beam, *e0* is the permittivity of free space, *V* is the applied voltage, and g is the gap between the beam and the ground electrode. Equation (1) is non-linear because the gap, g, depends on the displacement of the beam, i.e.,

$$g = g(u)$$

For a fixed-end, boundary conditions are imposed on the displacement and its slope, i.e.,

$$u=0,\quad \frac{du}{dx}=\bar{u},\quad x=0 \tag{2}$$

An RKPM formulation for Eqn (1) with fixed-boundary conditions at both ends is developed.

2.2 RKPM Formulation

Denoting *v* to be an arbitrary function, a weak-form to the strong form given in Eqn (1) can be developed as by Aluru[31] from the following equation as

$$\begin{aligned}&\int_\Omega v\left(\frac{\rho}{EI}\right)u,tt\,d\Omega+\int_\Omega v(u_{,xxxx}-P(u))d\Omega\\&+\int_\Gamma \delta\lambda(u_{,x}-\bar{u}_{,x})n\,d\Gamma=0\end{aligned} \tag{3}$$

where, $P(u)$ is the nonlinear right-hand side term from Eqn (1), Ω is the domain, Γ is the boundary of the domain, the boundary-integral in Eqn (3) is required for the imposition of the gradient boundary condition through a Lagrange multiplier technique, λ is the Lagrange multiplier, δλ is the variation of the Lagrange multiplier and *n* is the unit outward normal. Integrating Eqn (3) by parts and it was noted that

$$\lambda=-u_{,xx}\ ,\ \ \delta\lambda=-v_{,xx} \tag{4}$$

the weak formulation is summarised as

$$\begin{aligned}&\int_\Omega v\left(\frac{\rho}{EI}\right)u_{,tt}d\Omega+\int_\Omega v_{,xx}u_{,xx}d\Omega-\int_\Gamma v_{,x}u_{,xx}n\,d\Gamma\\&-\int_\Gamma v_{,xx}u_{,x}n\,d\Gamma=\int_\Omega vP(u)d\Omega-\int_\Gamma v_{,xx}\bar{u}_{,x}n\,d\Gamma\end{aligned} \tag{5}$$

To obtain a matrix form from Eqn (5), the displacement field *u* and the function *v* are approximated using the RKPM shape functions, i.e.,

$$u=\sum_{A=1}^{NP}N_A u_A \tag{6}$$

$$v=\sum_{A=1}^{NP}N_A v_A \tag{7}$$

where, N_A is the RKPM shape function. u_A and v_A are the unknowns associated with particle *A*.

The RKPM shape function is given as:

$$N_A(x)=C(x-x_I)w_d(x-x_I)\Delta V_I \tag{8}$$

The kernel function $w_d(x-x_I)$ is defined as:

$$w_d(x-x_I)=\frac{1}{d}w\left(\frac{x-x_I}{d}\right) \tag{9}$$

Denoting $y=(x-x_I)/d$, the cubic spline kernel function *w(y)* is defined as:

$$w(y)=\begin{cases}0 & ;y<-2\\ \frac{1}{6}(y+2)^3 & ;-2\le y\le -1\\ \frac{2}{3}-y^2\left(1+\frac{y}{2}\right) & ;-1\le y\le 0\\ \frac{2}{3}-y^2\left(1-\frac{y}{2}\right) & ;0\le y\le 1\\ -\frac{1}{6}(y-2)^3 & ;1\le y\le 2\\ 0 & ;y>2\end{cases} \tag{10}$$

where, $C(x,s)$ is the correction function and $w_d(x-s)$ is the kernel function. The correction function is expressed as a linear combination of polynomial basis functions in the following form:

$$\begin{aligned}C(x,s)\ &=\ c_0(x)+c_1(x)(x-s)+c_2(x)(x-s)^2\\&\quad +.....+c_N(x)(x-s)^N\end{aligned} \tag{11}$$

where, $c_0, c_1, c_2, ...c_N$ are functions of *x* which need to be determined. Substituting the RKPM approximations for *u* and *v* into the weak formulation, a nonlinear residual equation for a particle A can be written as:

$$R_A(u)=R_A^{dyn}(u)+R_A^{stat}(u) \tag{12}$$

where, $R_A^{dyn}(u)$ is the dynamic residual, and $R_A^{stat}(u)$ is the static residual

$$R_A^{dyn}(u)=\int_\Omega\left(N_A\sum_{B=1}^{NP}N_B u_{B,tt}\right)d\Omega \tag{13}$$

$$\begin{aligned}R_A^{stat}(u)\ &=\ \int_\Omega\left(N_{A,xx}\sum_{B=1}^{NP}N_{B,xx}u_B\right)d\Omega\\&-\int_\Gamma\left(N_{A,x}\sum_{B=1}^{NP}N_{B,xx}u_B n\right)d\Gamma\\&-\int_\Gamma\left(N_{A,xx}\sum_{B=1}^{NP}N_{B,x}u_B n\right)d\Gamma\\&-\int_\Omega\left(N_A P(u)\right)d\Omega+\int_\Gamma N_{A,xx}\bar{u}_{,x}n\,d\Gamma\end{aligned} \tag{14}$$

The integrals in Eqn (14) are evaluated through a simple quadrature rule.

2.2.1 *Static Analysis*

For static analysis, the dynamic residual term in Eqn (14) is not considered and the residual $R_A(u)$ is simply the static residual. Eqn (14) (without the dynamic residual term) can then be solved by employing a Newton's method. The displacement increment within each Newton iteration can be computed by solving the following equation:

$$\frac{\partial R_A^{stat}}{\partial u_B}\Delta u_B = -R_A^{stat}(u) \tag{15}$$

In matrix form, Eqn (15) can be stated as

$$J(u)\Delta u = -R_A^{stat}(u) \tag{16}$$

where $J(u) \in R^{(NP\times NP)}$ is the Jacobian matrix, $\Delta u \in R^{(NP\times 1)}$ is the displacement increment vector, and $R^{stat}(u) \in R^{(NP\times 1)}$ is the static residual vector. The entries of the Jacobian matrix are given by

$$\begin{aligned} J_{AB}(u) \;=\; & \int_\Omega N_{A,xx}N_{B,xx}d\Omega - \int_\Gamma N_{A,x}N_{B,xx}nd\Gamma \\ & -\int_\Gamma N_{A,xx}N_{B,x}nd\Gamma - \int_\Omega N_A(\partial P/\partial u)N_B d\Omega \end{aligned} \tag{17}$$

where J_{AB} is the A^{th} row and B^{th} column element of J.

3. NUMERICAL RESULTS AND DISCUSSIONS

The static pull-in values obtained through RKPM analysis and *Insellisuite* MEMS CAD are reported. Fixed-beam above the bottom electrode is considered for the analysis at a frequency of 40 GHz. The beam is 300 µm long, 80 µm wide, and 1.5 µm thick. The initial gap (g_o) between the beam and the bottom electrode is 1.5 µm. A Young's modulus of 80 GPa and a mass density of 19300 kg/m^3 are employed. For boundary conditions, the displacement and the slope are assumed constrained at both ends of the beam. This device is simulated by employing 101 particles.

Figure 1 shows the deflection of the beam as a function of a series of applied voltages obtained using RKPM analysis. As the potential difference between the beam and the bottom electrode increases, the beam deflects and the gap between the electrode decreases. At a certain voltage, defined as the pull-in voltage, the beam becomes unstable (at a critical gap height of 2/3 g_o) and collapses onto the bottom electrode. For the beam under consideration, the pull-in voltage is computed to be 34.08 V.

The pull-in value reported by Muldavin and Rebeiz[3] is 35V. and the simulated result using Intellisuite is 32.5 V. as shown in Figs 2 and 3.The electrostatic analysis of the switch can also be done once the displacement is obtained. As in Fig. 4, the contact capacitance is about 1.1 pF, which agrees well with the reported value[3].

4. CONCLUSIONS

Meshless analysis of RF MEMS shunt switch based on RKPM is presented by comparing the pull-in voltages

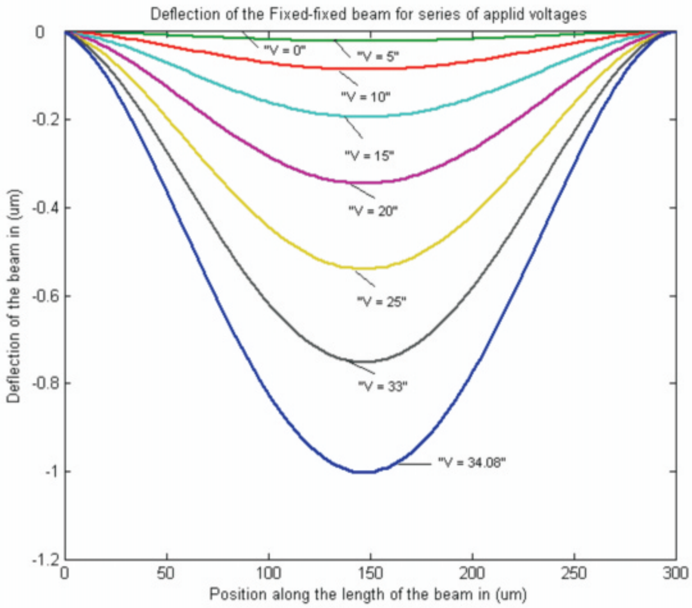

Figure 1. Deflection of CPW fixed-fixed beam for a series of applied voltages obtained using RKPM analysis. The pull-in voltage was 34.08 V.

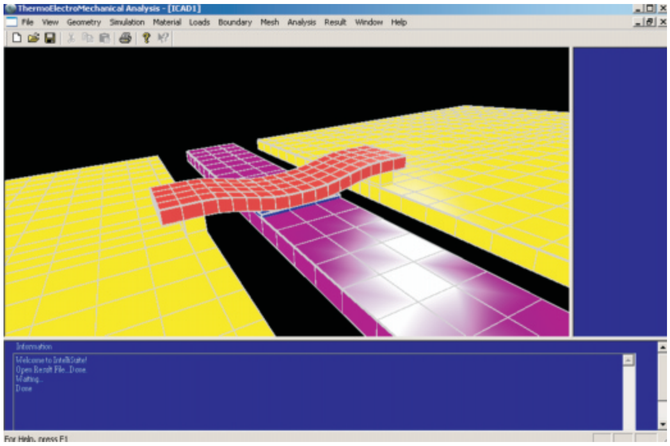

Figure 2. Screen shot of CPW switch showing the pull-in effect. The pull-in voltage was 32.5 V.

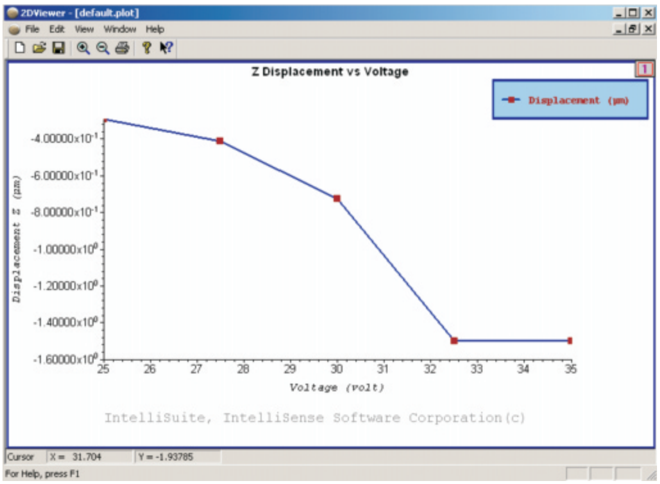

Figure 3. Reduction in gap height as a function of the applied voltage.

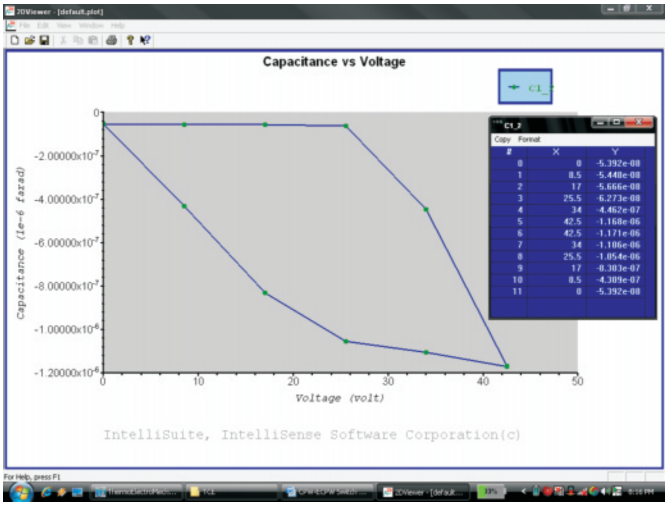

Figure 4. Capacitance *vs* voltage characteristics of the switch during pull-down and release.

and peak deflections with the reported datas. Numerical results presented for 3-D electromechanical structure converges within 30 min for 15 iterations and mesh-based simulation takes 1 h for 5 iterations to converge.

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