Numerical Modeling of the Transient Behavior of MEMS Structures Involving Motion in Arbitrary Directions

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Abstract
The adaptive body fitted grid generation method for moving boundaries is applied to the analysis of MEMS-based variable devices involving motion in arbitrary in-plane directions . MEMS technology is growing rapidly in the RF field and the accurate design of RF MEMS structures that can be used for phase shifting or reconfigurable tuners requires the computationally effective modeling of their transient and steady-state behavior including the accurate analysis of their time-dependent moving boundaries. The new technique proposed in this paper is based on the finite-difference time-domain method with an adaptive implementation of grid generation. Employing this transformation, it is possible to apply the grid generation technique to the analysis of geometries with time-changing boundary conditions. A variable capacitor that consists of two metal figures that can move in arbitrary directions of the plane is analyzed as a benchmark. The numerical results that express the relationship between the velocity of the plates and the transient capacitance are shown for oblique in-plane motions and the transient effect is accurately modeled.

1. Introduction

An accurate knowledge of the electromagnetic field evolution around a moving or rotating body is very important for the realization of new optical devices and microwave devices, such as the RF-MEMS structures used in phase-shifters, couplers or filters [1,2]. In this paper, we propose a new numerical approach for the analysis of this type of problems that overcomes the limitations of the conventional time-domain techniques[3]-[9] . By using a transformation with a time factor, it is possible to apply the grid generation technique of [10] to the time-domain analysis of the moving object. With such a grid, the FD-TD method can be solved very easily on a "static" (time-invariant) rectangular mesh regardless of the shape and the motion of the physical region。 It is a feature that makes the new method especially useful for analyzing moving objects of arbitrary shape. In this paper, the new simulation method is applied to the analysis of a two-dimensional MEMS variable capacitor with fingers that move arbitrarily in a 2D plane.

2. Two- Dimensional Variable Capacitor with Finger Motions to Arbitrary in-plane Directions

The geometry considered here is shown in Fig.1. Under the combined effect of mechanical and electrical force, the two plates are assumed to move with different velocities in arbitrary directions of the plane. In the case of two-dimensional TM-propagation, as shown in Fig.1, the only nonzero components are Ex, Ey, Hz, and they exhibit a time evolution expressed by:

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}\right) \tag{1}$$

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y} - J_x\right) \tag{2}$$

$$\frac{\partial E_y}{\partial t} = -\frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial x} + J_y\right) \tag{3}$$

where ε, μ are the constitutive parameters of respective medium. Fig.1 shows the configurations of the physical and of the computational regions. The interdigitated fingers are assumed to move in arbitrary directions in the *xy*-plane respectively with velocities v and u, respectively and in the direction shown by the angles θ_v and θ_u. Using a coordinates' transformation technique, the time-changing physical region (x,y,t) can be mapped to a time-invariant computational domain. For the geometry of Fig.1, the transform equations between the physical and the computational regions are chosen as:

$$\xi = \frac{x - h_n(t)}{h_{n+1}(t) - h_n(t)} \tag{4}$$

$$\eta = \frac{y - g_m(t)}{g_{m+1}(t) - g_m(t)} \tag{5}$$

$$\tau = t \tag{6}$$

where $n=1,2,3$, $m=1,2,3$ and $h_1(t), h_2(t), h_3(t), h_4(t)$, $g_1(t), g_2(t), g_3(t), g_4(t)$ are written in the following form assuming that the plate move with constant velocities for the whole time of their motion.

$$h_1(t) = x_1 + (v\cos\theta_v)t \tag{7}$$

$$h_2(t) = x_2 + (u\cos\theta_u)t \tag{8}$$

$$h_3(t) = x_3 + (v\cos\theta_v)t \tag{9}$$

$$h_4(t) = x_4 + (u\cos\theta_u)t \tag{10}$$

$$g_1(t) = y_1 + (u\sin\theta_u)t \tag{11}$$

$$g_2(t) = y_2 + (v\sin\theta_v)t \tag{12}$$

$$g_3(t) = y_3 + (v\sin\theta_v)t \tag{13}$$

$$g_4(t) = y_4 + (u\sin\theta_u)t \tag{14}$$

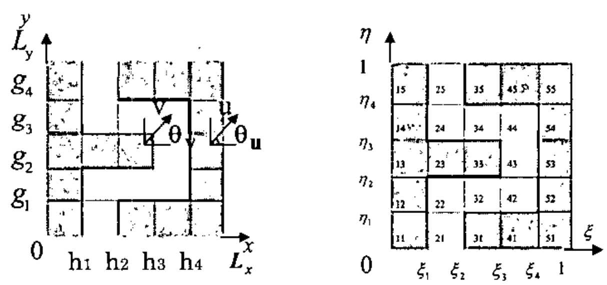

Fig1. Physical region and computational region

The functions $h_1(t), h_2(t), h_3(t), h_4(t), g_1(t), g_2(t), g_3(t), g_4(t)$ describe the movement along the x and y axis, respectively, and enable the use of a rectangular grid with stationary boundaries. The partial time-derivatives in the transformed domain (ξ, η, τ) can be expressed in terms of the partial derivatives of the original domain (x,y,t) using eqs.(4)-(14). The FDTD technique can provide the time-domain solution of the rectangular (ξ,η,τ) grid. The stability criterion in this case is chosen as $c\Delta t \le \delta/\sqrt{2}$, where $\delta = \Delta x_0 = \Delta y_0$, assuming the grid is uniformly discretized in both directions. In general, δ is the minimum cell size for x and y directions.

3. Numerical Results

To validate this approach, numerical results have been calculated for a two-dimensional variable capacitor with the movement of the fingers in arbitrary in-plane directions. The grid includes 200x200 cells and, $L_x = L_y = L = 5\lambda$, $\Delta x = \Delta y = L/200$, $\Delta t = L/800c$. The initial plate separation is $L/5$ and the grid is terminated with Mur's absorbing boundary conditions. Fig.2 shows computational results of the time dependence of the instantaneous capacitance for velocity values in the range of $u = v = 2\times10^{-3}c$ to $u = v = 8\times10^{-3}c$, and for angles assumed to be $\theta_u = 0^\circ, \theta_v = 180^\circ$ (the plates move away from each other) from t= 0 time-step to t=60 time-step. The horizontal axis indicates the normalized time in time steps and the vertical axis indicates the value of the transient capacitance. The stationary value (v=u=0) is displayed as a reference, and shows a (smoother) time-variation due to the time evolution of the excitation function itself. Fig.3 shows the time dependence of the instantaneous capacitance for various velocity values, assuming that the plates approach each other from t=20 time-step to t=60 time-step. As the plates are approaching each other, the angles are $\theta_u = 180^\circ, \theta_v = 0^\circ$. Following this approach during the whole time-interval of the motion of the fingers, it is easy to perform an accurate analysis of the transient response of the structure and predict the ringing parasitic effects. Clearly the transient effect is more pronounced for the higher values of velocity. Fig.4 shows the time dependence of the transient capacitance for various velocity values, when the angles of the plate motions are $\theta_u = 30^\circ, \theta_v = -30^\circ$. The plates are

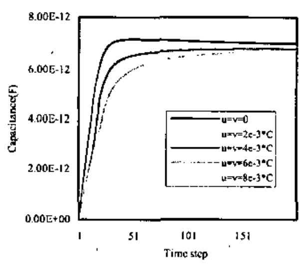

Fig2 Time dependence of transient capacitance for each velocity, where plates go away from t=0 time-step to t=60 time-step

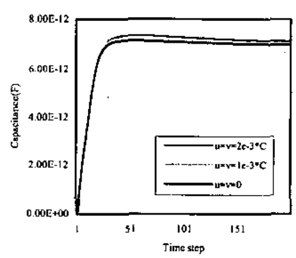

Fig.3 Time dependence of transient capacitance for each velocity, where plates approach each other from t=20 time-step to t=60 time-step

assumed to go away from each other from t=0 time-step to t=60 time step. Fig.5 shows the case when the plates approach each other with the angle $\theta_u = -30^\circ, \theta_v = 30^\circ$. Again, the transient effect for various velocities and motion directions can be accurately modeled.

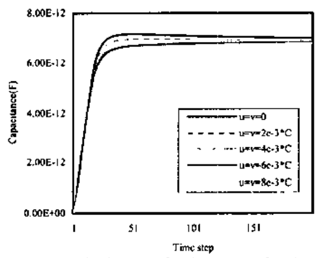

Fig.4 Time dependence of transient capacitance for each velocity, where plates go away in the direction of 30 degree from t=0 time-step to t=60 time-step

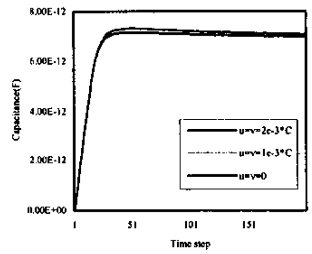

Fig.5 Time dependence of transient capacitance for each velocity, where plates approach each other in the direction of 30 degree from t=20 time-step to t=60 time-step

4. Conclusions

A novel time-domain modeling technique for the modeling of the transient effect of MEMS structures with arbitrary in-plane motion of some of their parts has been proposed. This technique is a combination of the FDTD method and the body fitted grid generation technique. The key point of this approach is the enhancement of a space and a time transformation factor that leads to the development of a time-invariant numerical grid. The numerical results of the relation between the capacitance and the velocity of arbitrary motions in arbitrary directions are shown for a MEMS capacitor and demonstrate its unique computational advantages in the modeling of microwave devices and/or optical devices with moving boundaries.

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