Triangle Transducer for Micro Electro Mechanical Systems (MEMS) Simulation in ANSYS Finite Element Program

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ABSTRACT

The paper introduces a new methodology with a distributed triangle transducer for the strongly coupled simulation of micro electro mechanical systems (MEMS) in ANSYS Finite Element (FE) program.

Keywords: Micro Electro Mechanical Systems, (MEMS) Finite Elements, Transducer, Reduced Order Modeling

1 INTRODUCTION

The increasing functionality of the micro electro-mechanical systems (MEMS) leads to complex geometrical configurations of MEMS [1], which requires new efficient finite element (FE) modeling techniques. Lumped models [2] and semi-analytical approach [3] are no longer applicable for the devices, where fringing electrostatic fields are dominant, such as comb drives [4], electrostatic motors [5] and many others [6].

There has been several numerical methods proposed for the more accurate treatment of electro-mechanical systems by FE [7], boundary element and hybrid [8] methods: sequential physics coupling [7], reduced order fully lumped (Figure 1) [9], distributed mechanical with one 1D transducer [2] or distributed mechanical with multi-D transducer [10]. All these methods need some extra meshing/morphing, introduce simplifying assumptions, and may not be convenient to use.

This paper, after reviewing the history, introduces a distributed transducer with internal meshing/morphing, easy to use, and requires no assumptions. The new distributed transducer, TRANS109 element, can be used with both lumped and solid mechanical models (Figure 4).

2 HISTORICAL REVIEW

The sequential coupling between electrical and mechanical FE physics domains for MEMS analysis was introduced in ANSYS 5.6 [2,7] using the ESSOLV command macro. ESSOLV allows the most general treatment of individual physics domains. However, it can not be applied to small signal modal and harmonic analyses because a total system eigen frequency analysis requires matrix coupling. Moreover, sequential coupling generally converges slower.

To eliminate the shortcomings of ESSOLV, a strongly coupled transducer element, TRANS126 was introduced in ANSYS 5.6 [2,7]. Coupling between electrostatic forces and mechanical forces can be characterized by mapping the capacitance [11] as a function of the motion of the device. Completely modeling the fully coupled system, TRANS126 converts electrostatic energy into mechanical energy and visa versa as well as store electrostatic energy.

TRANS126 takes on the form of a lumped element with voltage and structural DOFs as across variables and current and force as through variables. Input for the element consists of a capacitance-stroke relationship that can be derived from electrostatic field solutions. The element can characterize up to three independent translation degrees of freedom at any point to simulate 3-D coupling. Thus, the electrostatic mesh is removed from the problem domain and replaced by a set of TRANS126 elements hooked to the mechanical and electrical model providing a reduced order modeling (ROM) of a coupled electrostatic-structural system (Figures 1 and 2).

Even with the strongly coupled TRANS126 we experienced convergence issues when applied to the difficult hysteric pull-in and release analysis [10]. We attributed the cause of the problem to the negative total system stiffness matrix and resolved it in ANSYS 5.7 using the augmented stiffness method.

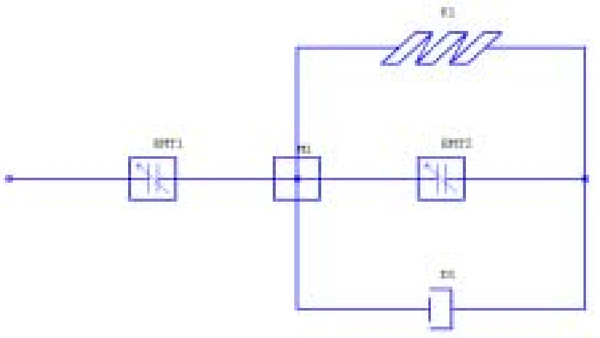

Figure 1: ROM using lumped elements.

Whereas TRANS126 allows treatment of all kinds of analysis types, including prestressed modal and harmonic analyses, furthermore the Newton - Raphson nonlinear iteration converges quickly and robustly with TRANS126, it is limited geometrically to problems when the capacitance can be accurately described as a function of a single degree of freedom, usually the stroke of a comb drive.

In a bending electrode problem, like an optical switch, obviously, a single TRANS126 element can not be applied. Fortunately, when the gap is small and fringing is not significant, the capacitance between deforming electrodes can be practically modeled reasonably well by several capacitors connected parallel. The EMTGEN (electro mechanical transducer generator) command macro, introduced in ANSYS 5.7 can be applied to this case.

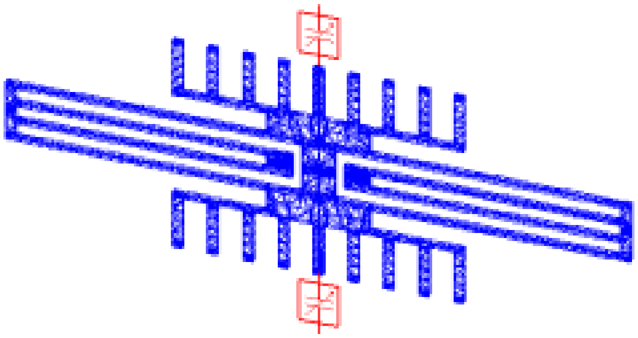

Figure 2: FE model of comb drive with TRANS126.

However, a new treatment is necessary for more general geometries. This paper is introducing a 2D transducer, TRANS109, developed in ANSYS 6.0 beta version, to fill the gap between ESSOLV and TRANS126 capabilities. The new strongly-coupled field transducer benefits from both methods. The TRANS109 element is strongly coupled, but neither assumptions are made regarding the electrostatic field nor is the capacitance-stroke relationship required [2]. The principle of virtual work lays in the basis of the element formulation coupled with the electrostatic degrees of freedom.

3 FORMULATION

The element potential energy is stored in the electrostatic domain. The energy change is associated with the change of potential distribution in the system, which produces structural reaction forces. TRANS109 takes the form of a triangle field FE with electrical potential, VOLT and structural displacement, UX and UY, degrees of freedom (see Figure 4).

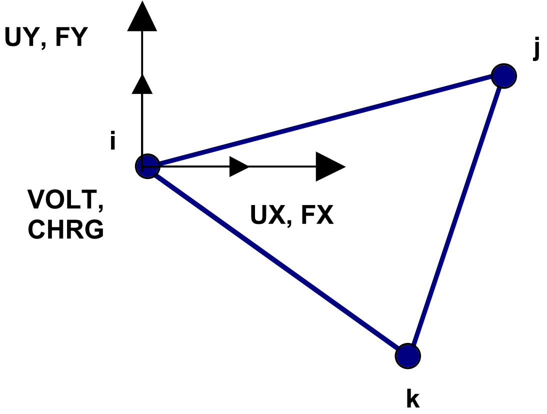

Figure 3: Trans109 DOFs and forces.

The reaction "forces" are electrical charge, CHRG, and mechanical force, FX and FY. The FE formulation of TRANS109 transducer follows standard Ritz-Galerkin variational principles which ensure that it is compatible with regular finite elements. The electrostatic energy, *W*, is

$$W = 1/2 v^t C v \tag{1}$$

In (1), *v* is the vector of nodal voltages, superscript *t* denotes transpose, and *C* is the element capacitance matrix. The electrostatic charge, *q*, can be obtained as

$$q = Cv \tag{2}$$

The capacitance matrix, *C*, depends on the element geometry. The nodal electrostatic reaction force, *f*, can be calculated by the virtual work principle:

$$f = 1/2 \frac{dW}{du} \tag{3}$$

In (3), u is the vector of nodal displacements. At equilibrium, the electrostatic forces between each transducer elements as well as transducers and mechanical elements balance each other. The mesh, including the air region, deforms so that the force equilibrium be obtained. The mesh is morphed, which means that no new nodes or elements are created, but the displacements of the original nodes are constantly updated according to the electro-structural force equilibrium (see Figure 4). This procedure is highly non-linear and huge displacements are allowed for arbitrary uneven mesh.

4 EXAMPLE PROBLEMS

A comb drive transducer is modeled using the new transducer element [4]. The deforming solid body is meshed by regular ANSYS structural elements, for example SOLID42. The air region is meshed by TRANS109. As opposed to EMTGEN, the air region is not restricted to the gap, thus, fringing fields are accurately simulated. Contact features can be modeled by contact elements, for example CONTAC12. Electrical features can be modeled by lumped electric elements. Figure 4 shows details of the original and deformed FE mesh, which is refined near the corners. The potential distribution is depicted in Figure 5. The theoretical [4] and computed values of driving electrostatic force are presented in Table 1 (where L is the comb drive finger overlap).

Overlap	Driving force (Target value = 8.5E-5 N)
0.1 L	8.38E-05 N
0.5 L	8.39E-05 N
0.8 L	8.57E-05 N

Table 1. Driving comb drive force.

The next example is the model of two overlapped narrow electrodes. Because of the thin geometry of electrodes, the fringing effects are significant. The potential distribution is shown in Figure 6. The electrostatic attractive forces are obtained not by the Maxwell stress tensor, rather by much more accurate virtual work principle, which are computed as element reaction forces. The computed forces are Fx = 0.313E-04 and Fy = 0.301E-03. Without fringing fields, one would get: Fx = 0.354E-04 and Fy = 0.283E-03 – a huge difference. The horizontal component of the force (Fx) at the electrode tip node provides 99.9% of the total horizontal force. The meshing around the tip has to be very fine. Despite the difference in size of the elements, the morphing is successful.

The new TRANS109 element is effective in solving the pull-in/release hysteric beam-bending problem with contact [12]. This is numerically difficult problem because of the bifurcation of static equilibrium, which may lead to stability issues. The tip vertical displacement vs. potential drop is depicted in Figure 7. Good agreement can be observed with [12] and the ESSOLV results.

TRANS109 can be also applied in a transient analysis, such as simulation of the parallel plate transducer with the current impulse load [13]. The results agree very well with [13] and Runge – Kutta time integration (see Figure 8). Note, that TRANS109 works robustly with charge, voltage, force or displacement load.

5 CONCLUSIONS

TRANS109 provides an easy to use field transducer element for modeling strongly coupled electro mechanical interaction. The new element is compatible with structural solid and lumped FE models and thus can be effectively used for analysis of complex distributed and ROM electro mechanical systems.

TRANS109's application range is as general as the sequential ESSOLV procedure, but converges more robustly with about an order of magnitude smaller number of iteration. TRANS109 has much more general geometry than gap transducer TRANS126 but less robust and needs more iterations to converge.

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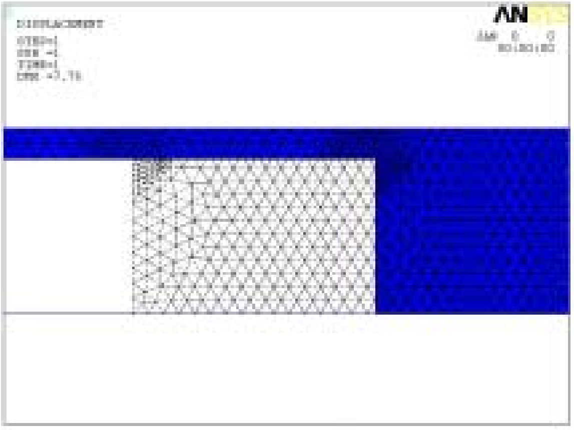

Figure 4. Original and deformed mesh.

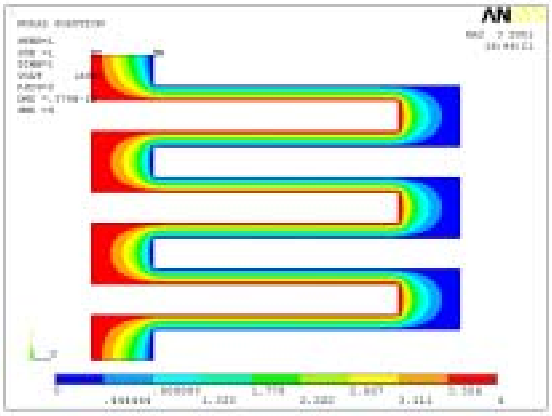

Figure 5. Potential on deformed comb drive.

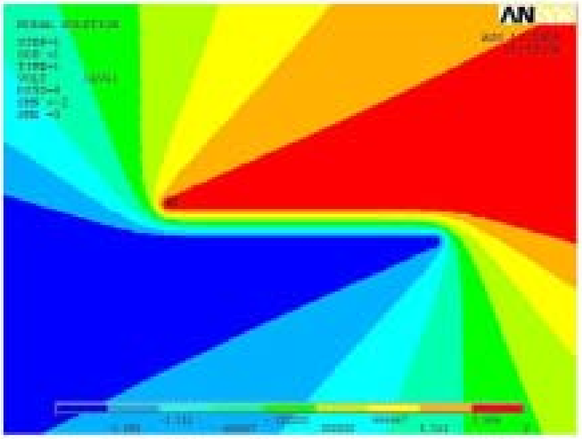

Figure 6. Two overlapped electrode-fringing field.

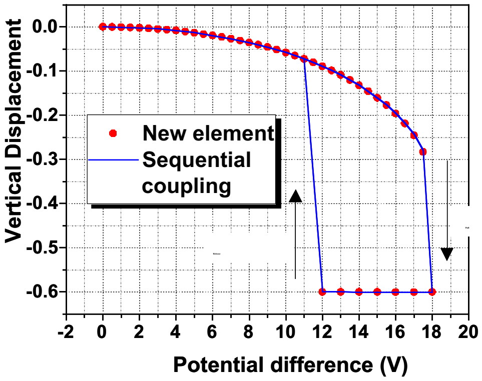

Figure 7. Hysteresis loop (pull-in/release).

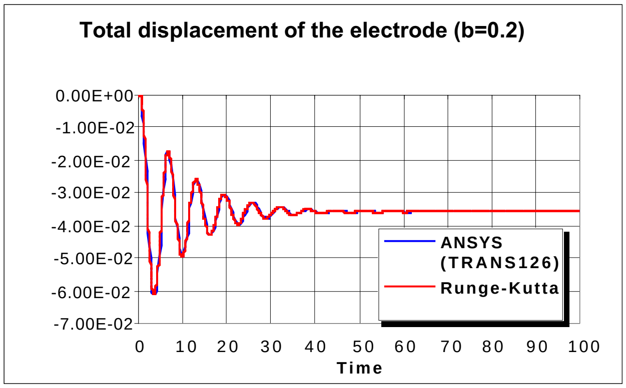

Figure 8. Transient response of the parallel-plate electrode.