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Sensors and Actuators A 136 (2007) 403–411
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Development and verification of 2D dynamic electromechanical coupling solver for micro-electrostatic-actuator applications

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Received 22 April 2005; received in revised form 11 October 2006; accepted 20 October 2006
Available online 20 November 2006

Abstract

The construction, analysis, and simulation of a dynamic electromechanical coupling module, *DEDS FEM*, is presented in this paper. This module integrates an electrostatic distribution subroutine with commercial finite element packages to explore the influence of electrostatic load imposed on mechanical dynamics and it has been successfully verified by a lumped analytical model, a convergence test of a fixed–fixed beam example, and a RF MEMS switch case study. For 2D case, it shows that the *DEDS FEM* can achieve the same accuracy as that performed by differential quadratic method (DQM) and finite difference method (FDM) but with a significant improvement in the user friendliness and the capability in handling complicated geometries and material constitutive laws. In addition, by this approach, it allows users to handle problems with more complicated constitutive law of materials, boundary conditions, and loading manners and it should be useful in the conceptual design analysis and device longevity study for many electrostatic driven MEMS devices such as digital mirror displays (DMD), RF MEMS relays, and optical switches.

Keywords: MEMS; Electromechanical coupling; Finite element analysis; RF switches

1. Introduction

Electromechanical coupling is a common phenomenon existing in electrostatically actuated microelectromechanical systems (MEMS) such as optical switches [1], micro pumps [2], accelerometers [3], and mirrors [4]. Most of these systems contain certain parallel-plate-like components for the purpose of electrostatic actuations. From the mechanical (ME) perspective, these parallel plates provide linear or nonlinear attractive forces to actuate moving structures. On the other hand, for the electrical (EE) domain, these MEMS structures can be treated as variable capacitors and can be used for impedance matching in applications such as radio-frequency (RF) communications [5,6].

The performances of almost all of the above mentioned devices depend on their dynamic characteristics and responses. Taking MEMS mirrors as a specific example, it is desired to have a fast switching rate to increase the scanning speed during operation, while lower power consumptions and longer service life are also desirable. This *speed-energy-life* coupling problem can only be solved and optimized through a complete electromechanical coupling dynamic analysis.

At this moment, several academic investigations on solving dynamic EM coupling problems for MEMS structures have been reported. McCarthy et al. [7] applied the finite difference methods (FDM) to analyze the switching period and transient response of gold RF MEMS switches fabricated using electrodeposition. Their analysis results matched the experimental data well at higher applied voltage but exhibited considerable inconsistency if the applied voltage is near the *pull-in* threshold. Kuang and Chen [8] utilized the differential quadrature method (DQM) [9–11] to evaluate the spring softening effect and to predict the natural frequency of a fixed–fixed beam subjected to electrostatic loading and the results agree with the experimental data [12] in large extent. Although those self-programmed FDM and DQM codes can yield fair results for specific electromechanical coupling problem, without the help of commercial finite element or CFD packages to provide supports in other aspects such as material constitutive laws and multi-disciplinary analysis, the effect of both the self-programmed FDM and DQM are limited to cases with simple geometry and material behavior and the problem formulations are quite problem-dependent. On the other hand, although most of the commercial MEMS

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0924-4247/$ – see front matter
doi:10.1016/j.sna.2006.10.042

design packages, such as CoventorWare [13], Intellicad [14], and MEMS Pro [15], as well as some general purpose finite element packages such as ANSYS and CFDRC, have certain level of capability in solving electromechanical coupling problems. However, in general, they are usually expensive and might not affordable for many users. In addition, their modular design implies that they are interested in certain specific problems such as *pull-in* voltage and hysteresis estimation. If one is interested in a novel problem involving electrostatic actuation (example is given below), it would be difficult to conduct the analysis by these packages.

Note that field solvers (FEM, BEM, etc.) are not the only and certainly way for performing EM coupling analysis. Much research has been carried out on EM MEMS behavior models, which are based on analytical models, written in a hardware description language (HDL) and implemented into electronic network simulators [16–18]. They can perform efficient simulations for predicting system performances. However, this approach is usually used for finding the system dynamics model of the system for performance prediction. In addition, the behavior models usually require certain finite element, finite difference, or boundary simulations to calibrate them [19]. Furthermore, it may not be able to handle other aspects such as stress, strain, temperature, and wave propagation, etc.

Consider a generic problem of a MEMS structure such as a switch, made of anisotropic brittle material, is subjected to electrostatic force and heat flux input and it would contact dynamically with an elasto-plastic material with considerable strain hardening effect and the issue for concern is the longevity of the structure under operation. This type of problem involves many variables from different domains and is certainly too complicated to be solved by self-developed codes. On the other hand, it is also difficult to be analyzed by the MEMS analysis tools because this is not a well-classified problem. Finally, the HDL or equivalent circuit approach cannot handle the structure reliability issues.

One approach to solve the problem illustrated above is to use an approximated relationship to model the electrostatic force and integrated the approximate mode into general-purpose finite element packages. By this approach, it is possible to utilize the capability of those FE packages to analyze the problem illustrated above. In our previous study, two electromechanical coupling solvers, EMS (electro-mechanical sequential solver) and EDS (electrostatic distributed load solver), have been demonstrated [20]. And for the investigated surface micromachined structures in [20], case studies using both solvers indicated that a 2D finite element EM coupling model could achieve the same accuracy as that performed by a full 3D EM coupling analysis by MEMS CAD but with significantly less computational efforts. In these two solvers, EDS is more flexible since it is essentially a finite element procedure with an embedded electrostatic distributed load subroutine. Therefore, it is possible to extend this method in solving dynamic problems. The flow and feasibility study of the new procedure, called dynamic electrostatic distributed load solver (*DEDS*), is presented in this article. As shown in Fig. 1, the concept of *DEDS FEM* is straightforward: by modeling the electrostatic force as an equivalent pressure load and serving as an embedded distributed load subroutine in finite element code and to perform the necessary dynamical analysis. Note that as also shown in Fig. 1, by integrating it with standard FE packages, it allows users to handle problems with more complicated constitutive law of materials, boundary conditions, and loading manners.

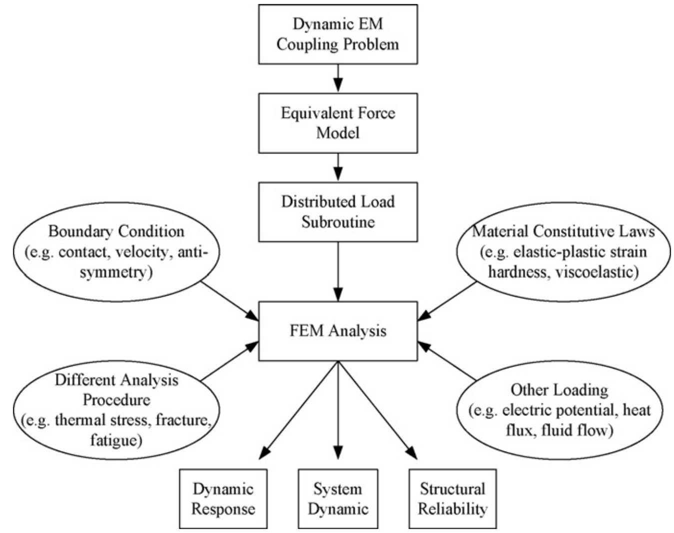

Fig. 1. The flowchart of the *DEDS* method and its ability to integrate with FEM packages.

Although both *EDS* and *DEDS* methods can handle 3D problems to a certain extent, we shall restrict our discussion in 2D problems, which are realistic simplification in many surface micromachined MEMS structures. However, it is important to emphasis that the *EDS* and *DEDS* methods, like both the FDM and DQM reported earlier, are focus on the mechanical domain only. As a result, for those applications concern the influence of mechanical variable on the electrical responses, these solvers are not appropriated. However, for many other applications, where the major concern is in mechanical dynamic responses, these solvers should be quite useful.

The rest of the paper addressed the construction, validation, and application of the *DEDS* in detail. In Section 2, the construction of the *DEDS* is illustrated, followed by a detailed verification process and a RF MEMS switch example presented in Sections 3 and 4, respectively. The performance, characteristics, and other possible applications are then discussed in Section 5. Finally, Section 6 concludes this paper.

2. Model description

To solve a general dynamical EM coupling problem for MEMS applications, we shall consider fields such as structure dynamics, fluid mechanics, electrostatics, and even mechanical properties of materials. Such a multi-disciplinary problem can be solved by iteration between each domain-specified problem or by reducing each disciplinary to their equivalent mechanical model.