MULTISCALE AND REDUCED ORDER MODELS FOR THE RELIABILITY ANALYSIS OF POLYSILICON INERTIAL MEMS

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Summary Inertial micro electro-mechanical systems (MEMS) developed for mobile applications, like accelerometers and gyroscopes, are often exposed to severe dynamic excitations. Reliability analysis of such microsensors therefore demands for powerful, accurate and fast numerical tools to provide prognoses of possible failure events. Within a purely mechanical frame, we present here multiscale and physically-based reduced order models conceived to simulate the effects of shocks on polysilicon inertial MEMS, accounting for the phenomena that occur at the package, sensor and polysilicon film (constituting the movable MEMS parts, prone to failure) length-scales.

INTRODUCTION

Inertial MEMS for mobile applications are often subjected to shock loadings, mainly due to drops or mishandling of the devices [1]-[2]. While sensors are designed to work under accelerations amounting to a few g (g being the gravity acceleration), shocks typically cause acceleration peaks exceeding 10^5 g but lasting tens or hundreds of ns only, depending on the sensor layout. To avoid unexpected failures and enhance the design, if necessary, a reliability analysis of such microsensors is therefore in need of numerical tools able to provide accurate resolutions of the stress/strain fields at the polysilicon film level.
During the last few years, we developed a multiscale framework to attack the problem [3-9]. Within this frame, prognostic analyses of shock-induced failures in polysilicon inertial MEMS account for physical processes occurring at several length-scales. Trying to simplify the approach, three main scales can be singled out [3-5]: a macroscopic one, wherein the whole package is considered; a mesoscopic one, wherein the whole sensor is analyzed; a microscopic one, wherein the local failure processes in the polysilicon film are modeled. To further reduce the computational burden without affecting the accuracy of the results, in [9] we also started addressing the reduce order modeling of the movable parts of the sensors (at the meso-scale), by resorting to beam-plate models of the whole device.
In this work, we present an overview on the main features of the multiscale and reduced order modeling approaches, in order to highlight the open issues and to focus on the work in progress.

MULTISCALE ANALYSIS

The length-scales involved in the shocked-induced response and failure of polysilicon inertial MEMS range from mm (typical size of the sensor package) down to nm (length of the process zone in the cracking polycrystalline silicon film). A trivial, homogeneously refined meshing in finite element simulations of these events would be therefore too expensive; a smart way to attack the problem is by resorting to a (decoupled, top-down) multiscale approach.
In case of a drop, at the macro-scale the packaged device is assumed to strike the target body, which is viewed as massive. While bouncing off the target, the device experiences a rigid body-like translational and rotational movement; this motion is characterized by a long time scale (several μs), and can be superseded by much faster phenomena linked to stress waves propagation.
At the meso-scale MEMS vibrations are induced by displacements of the MEMS anchor(s), and are damped by its interaction with the surrounding fluid. The aim of analyses at this scale is to link impact features to possible failure events, assumed to occur where the maximum principal tensile stress in the polysilicon film reaches a critical threshold.
At the micro-scale the dissipative mechanisms, consisting in the nucleation and propagation of inter- and trans-granular cracks in the brittle polysilicon film, are investigated into details through a cohesive approach. A crack is therefore assumed not to abruptly show up, but instead to progressively form and grow due to strength reduction in the process zone region(s). Since analyses have to account for the actual morphology of the polycrystalline film, or for an appropriate representation of it, the hypothesis of homogeneous bodies does not hold true at this scale.
The above three-scale approach allowed to accurately match the actual failure location and mode in a uni-axial accelerometer, see Fig. 1 and [3-5]. Those results were obtained by considering the morphology and mechanical properties of the polysilicon film to be random at the micro-scale, and hence adopting a Monte Carlo methodology [8]. Since this step turns out to be the most time consuming of the multiscale analysis, in [7] we provided a hybrid deterministic-stochastic upscaling scheme to define micro-structurally informed mechanical properties of a virtual homogeneous film, to be adopted at the meso-scale. Meanwhile, simplified analyses were carried out with a two-scale

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approach (avoiding the micro-scale Monte Carlo simulations) and compared to the full three-scale ones, showing good accuracy in the forecasted failure mode, see Fig. 2. Anyway, upscaling is still a main issue, since relevant stochastic morphology indicators and anisotropic, crystal lattice-induced properties of silicon both need to be properly accounted for to provide meaningful outcomes.

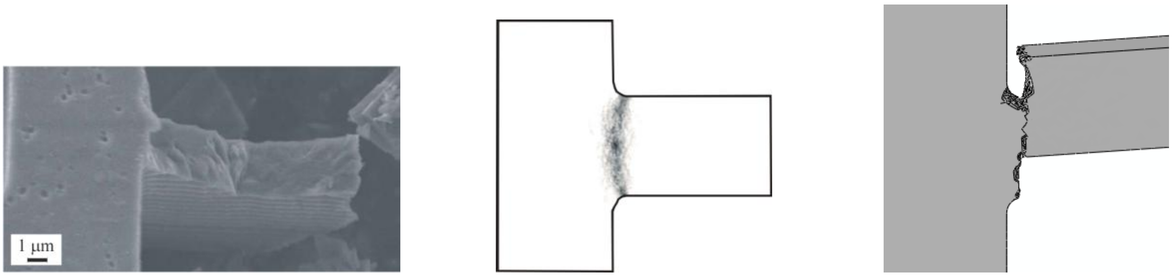

Fig. 1. Shock-induced failure of a uni-axial MEMS accelerometer:
(left) experimental evidence [5]; (center) stochastic, three-scale numerical forecast [9]; (right) deterministic, two-scale numerical forecast [9].

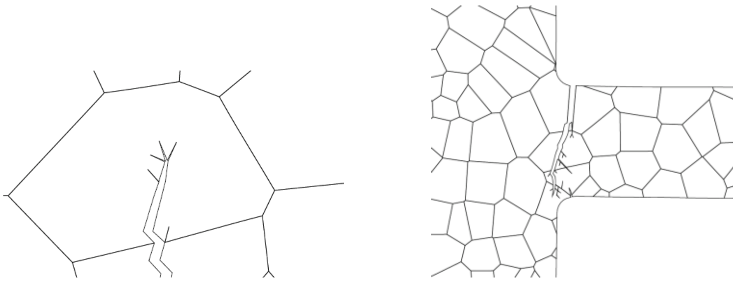

Fig. 2. Exemplary forecasted cracking events at the microscopic (polysilicon) length-scale, adapted from [8]:
(left) branching of a trans-granular crack; (right) crack pattern at percolation.

REDUCED ORDER MODELLING

To reduce the computational burden of the meso-scale finite element analyses, a reduced order modeling approach was developed by accounting for the main vibration modes involved in the sensor response to shocks. In the case of the already mentioned uni-axial accelerometer, we assumed the seismic plate to be rigid, and connected to the anchor point through deformable slender beams. Hence, the system can be reduced to two degrees of freedom only, in case of pure tensile or flexural deformations of the slender beams [6]: the out-of-plane translation of the plate, and the rotation of the plate around the beam axis. Contact conditions of the plate corners with the die and cap surfaces were considered to limit the plate motions; in the resulting nonlinear regime, the reduced order model allowed to strongly reduce the computing time, with a speedup factor approaching 50 on a common personal computer. Comparisons with the experimentally acquired output signals, caused by excitations in the range 50-5500 *g*, turned out to be encouraging.
An alternative approach, relying on proper orthogonal decomposition is now under study. By exploiting the structure in an ensemble of observations, a set of orthonormal bases for the discretized system are obtained through purely algebraic methods, like singular value decomposition. This approach will allow to reduce the computational costs, independently of the assumptions on the deformation modes of the suspension springs and of the seismic plate.

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