OBJECTIVE: To develop first-principles-based accurate analytical models that are critical to understanding the underlying physics. Also, to develop accurate analytical/asymptotic solutions that will serve in verifying and improving the computer simulations; Verification and Validation Thrust of PRISM Center.

- Non-linear effects present in an electro-statically actuated microbeam switch include:
  - Mid-plane stretching
  - Spring and damping effects of squeezed fluid film
  - Electrostatic actuation
  - Contact dynamics

- A relatively complete model must sufficiently account for the single and coupled physics, including:
  - Electrostatics: non-linear forcing, fringe-field effects
  - Thermal: variation of residual stresses, material properties
  - Mechanical: non-linear elastic behavior
  - Fluid: squeeze-film damping, shear damping and spring effects

- Extensions of current models, desired model capabilities.
  - Utilizing the Reduced Order Modeling approach (Younis et al. [2]), our models will include:
    - Response variations with temperature - This can be accounted for by modifying the residual stress and material properties;
    - Finite electrode width, fringe-field effects - Appropriate models have been proposed recently in Batra et al. [1] that incorporate modeling of fringe fields;
    - Material grain/microstructural effects, impact damage - These will be accounted for by making the material properties a function of the beam thickness, and possibly of previous cycles if good models for impact dynamics and damage are developed.
  - The best outcome will be an analytical model derived from first principles that predicts the dynamic behavior of MEMS, both over one cycle and as the device degrades/damages with repeated cycles.

- Current modeling efforts:
  - Most current models consider a thin beam or plate, include stretching nonlinearity, and one other aspect (i.e., squeeze film damping under a parallel plate electrostatics assumption);
  - Most successful analyses utilize reduced order models (e.g., Nayfeh);
  - GOAL: predict response - resonant frequencies, pull-in voltage, pre-bounce dynamics.

Illustrative Results:
- Model (Younis et al. [2]): Beam equation, parallel plate electrostatics, linear damping, residual stress and beam stretch.

\[
\begin{align*}
\frac{\partial^4 w}{\partial x^4} + \frac{\partial^2 w}{\partial t^2} + \frac{\partial w}{\partial x} & = [a_1 \Gamma(w, w) + N] \frac{\partial^2 w}{\partial x^2} + a_2 \chi(t) \frac{\partial^2 w}{\partial x^2} \\
\Gamma(f_i(s, t), f_j(s, t)) & = \frac{\partial^2 w}{\partial x^2} \frac{\partial^2 w}{\partial t^2} \quad c = \frac{c^2}{12}
\end{align*}
\]

n-mode ODE model obtained by Galerkin method:

\[
\begin{align*}
\sum_{i,j=1}^{n} \alpha_{ij} \frac{\partial^2 w_i}{\partial x^2} & + \sum_{i,j=1}^{n} \beta_{ij} \frac{\partial w_i}{\partial t} = \sum_{i,j=1}^{n} \gamma_{ij}(s, t) \frac{\partial w_i}{\partial x} \\
+ 2 \sum_{i,j=1}^{n} \delta_{ij} \frac{\partial w_i}{\partial x} & \quad \text{where } n=1,2,...,M \text{ and } w(x, t) - \sum_{i=1}^{n} \alpha_i(t) \chi(s)
\end{align*}
\]

Figures 3 and 4 compare model predictions with experimental data. Though the results are quite good, tuning is done for some unknown model parameters, e.g., c, to some data. There is need of more detailed modeling based on first principles so that all parameters of a device can be defined. The model shows the power of simplified models in predicting dynamics.

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