Stochastic multiscale modeling of stiction failure in MEMS

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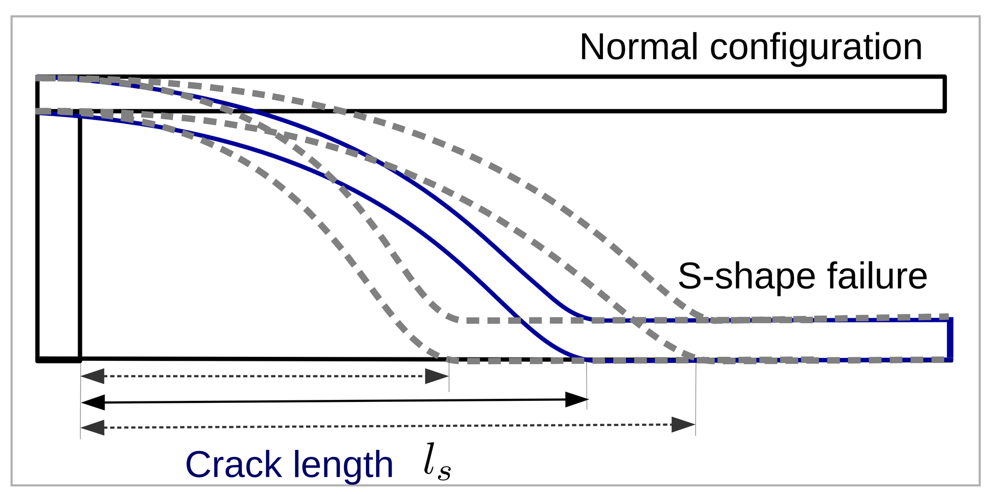
Introduction

- **Stiction** is a common failures in MEMS, in which two micro surfaces permanently adhere together, e.g. the stiction failure of micro cantilever beams.
- The problem is due to the adhesive forces, e.g. the **capillary forces**.
- The **adhesive contact force**, and **structural behaviors** suffer from **scatters**, due to the **roughness** of the contacting surfaces.

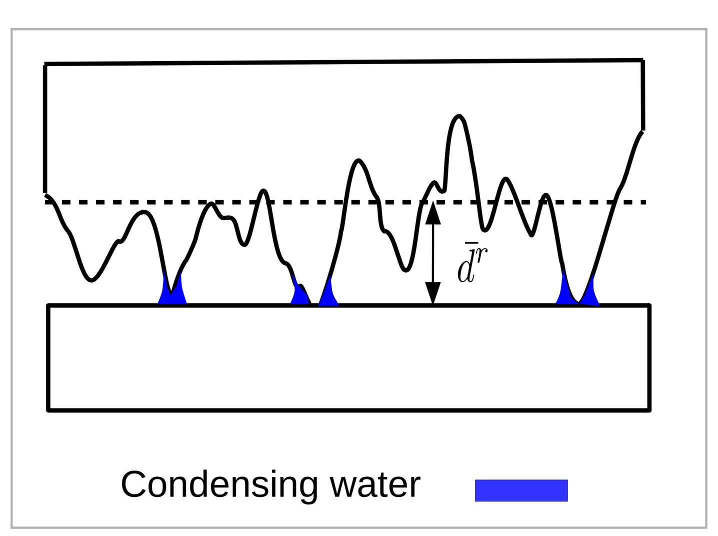
Aim

Construct a **numerical model**

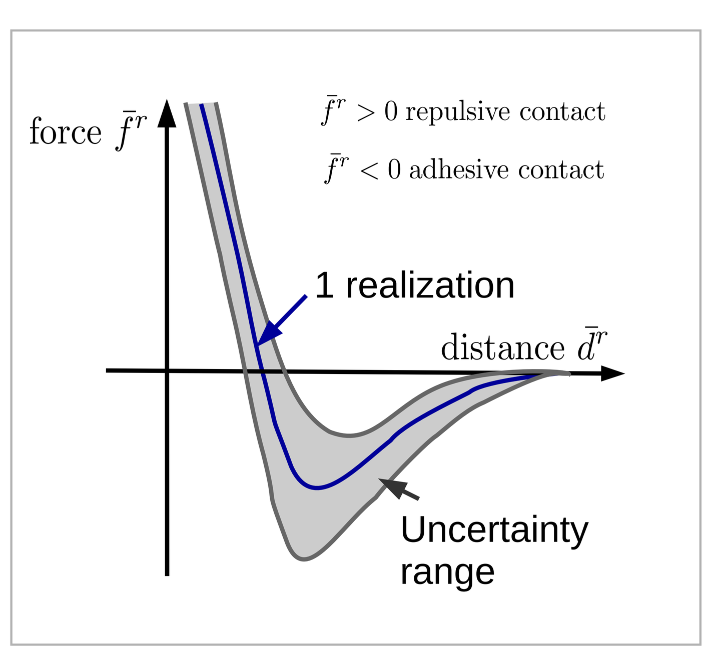
- to predict the **failure of MEMS devices** subject to adhesive stiction in a **probabilistic way**, e.g. to predict the probability of crack length in case of stiction failure of micro cantilever beam; and
- with an **acceptable computational cost**.



Failure of micro cantilever beams. The crack lengths are uncertain.



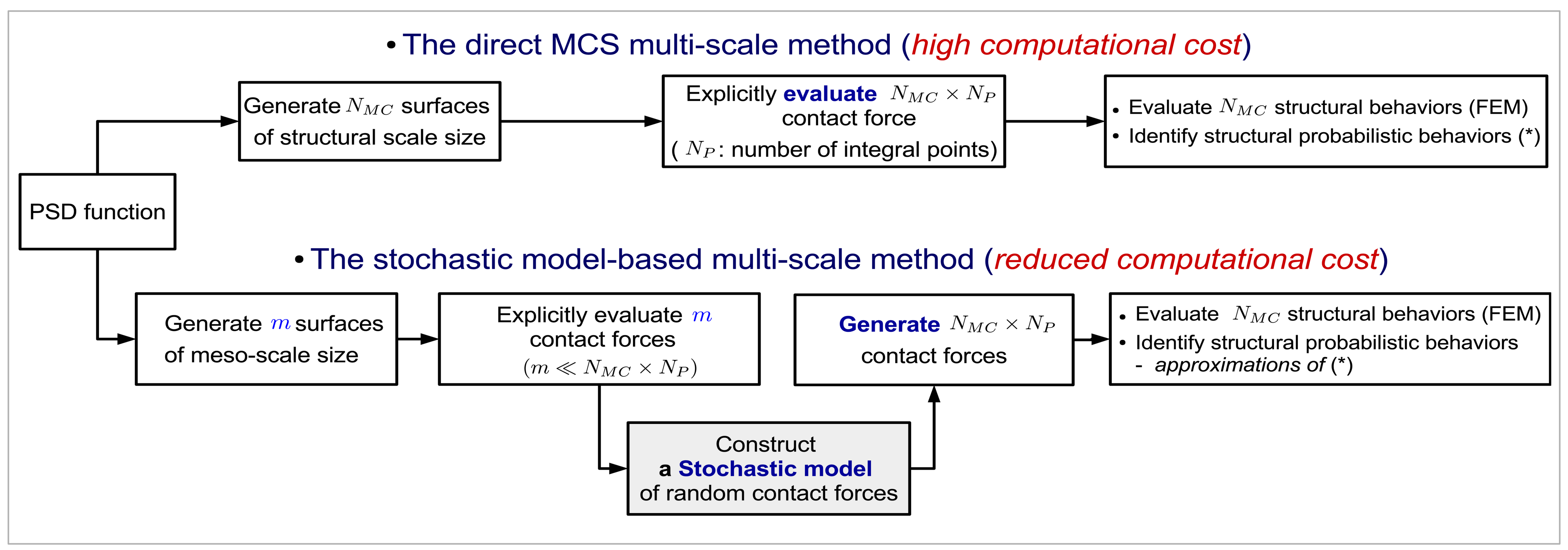
Zoom into the contact zone.



Random apparent adhesive contact forces.

Method

- **Direct Monte Carlo simulation (MCS) multiscale method.**
  - Characterize the contact rough surfaces using power spectrum density (PSD) and height distribution.
  - Generate N_{MC} surfaces with size of contact zone.
  - For each generated surface, at each integral point evaluate the corresponding meso-scale apparent contact force. (*)
  - Obtain the failure configuration for each generated surface.
  - \>\>\> Require **high computational cost** due to step (*).
- ***Proposed method*: Stochastic model-based multiscale method**
  - Construct a stochastic model of apparent contact force.
  - Each integral point is associated with a generated sample of the random apparent contact forces using the constructed stochastic model.
  - \>\>\> **Reduce computational cost.**

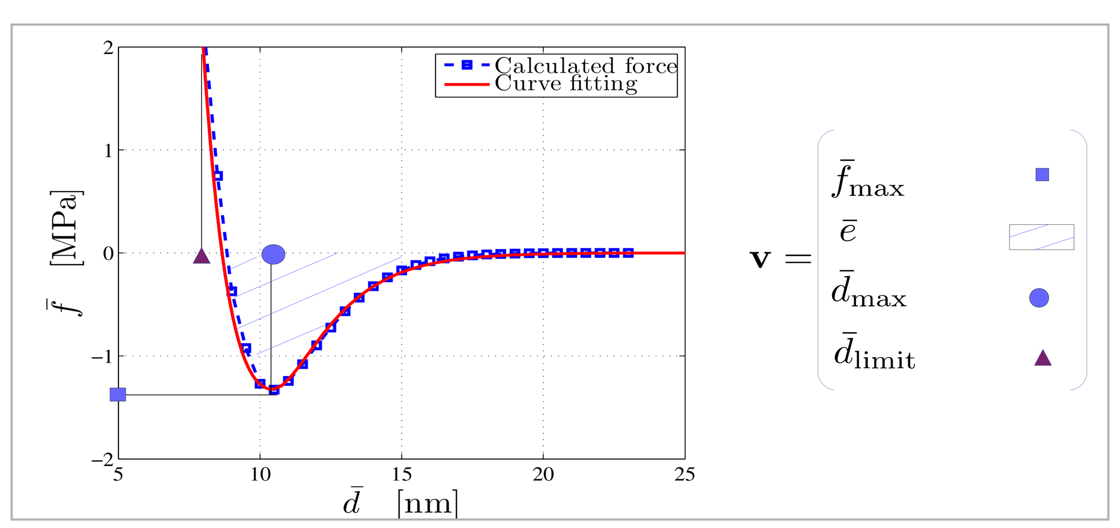


The two uncertainty propagation methods used to evaluate the probabilistic behaviors of structures involving adhesive contacts.

- **Construction of the stochastic model of random apparent contact forces based on generalized polynomial chaos expansion (gPCE) with 3 steps**
  - (i) Parametrization of the apparent contact forces using an analytical function derived from Morse potential,

$$\bar{f}(\bar{d}) = \Phi(\bar{d}; \mathbf{v}),$$

Force-distance curve; Curve fitting function; Parameter vector



Left: Curve fitting of a typical apparent contact force. Right: the parameter vector.

  - (ii) Data preprocessing procedures: accounting for the physical bounds (PBs), and dimension reduction using principle component analysis,

$$\underbrace{\mathbf{v}}_{\text{Constrained by PBs; 4-dimensional}} \xleftrightarrow{\text{Physical bounds treatment}} \underbrace{\mathbf{q}}_{\text{Unconstrained by PBs; 4-dimensional}} \xleftrightarrow{\text{Dimension reduction}} \underbrace{\eta}_{N_g\text{-dimensional } (N_g \leq 4)},$$

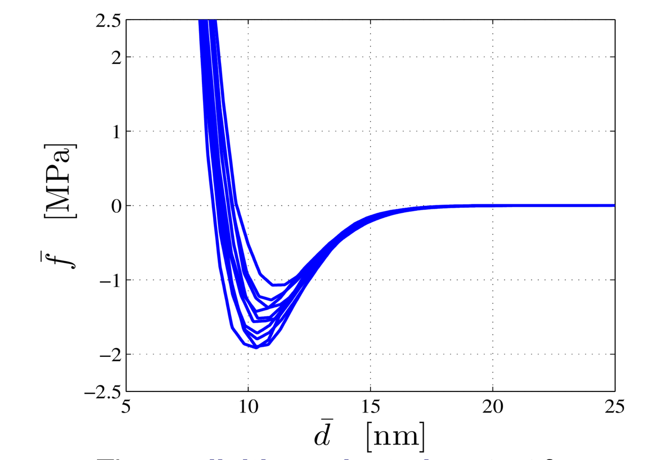
  - (iii) Representing the reduced dimension random vector by a truncated gPCE model,

$$\eta = \sum_{\alpha=1}^{N} \mathbf{c}_\alpha \Psi_\alpha(\xi).$$

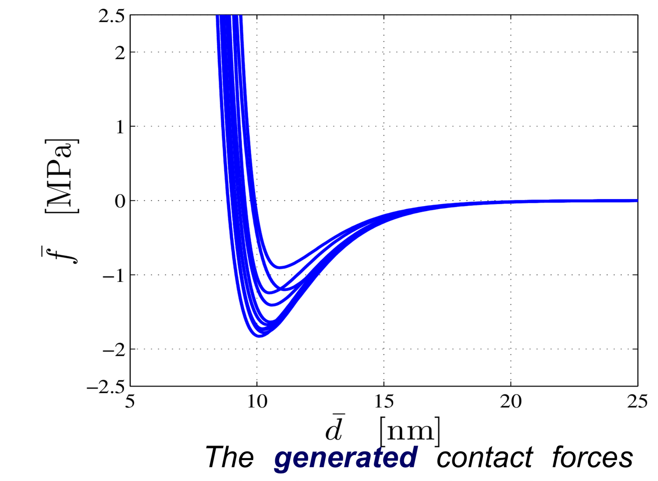
Coefficients to be identified ($\mathbf{c}_\alpha$); Legendre polynomials (Ψ_α); Uniform distributed random vector (ξ)

Results

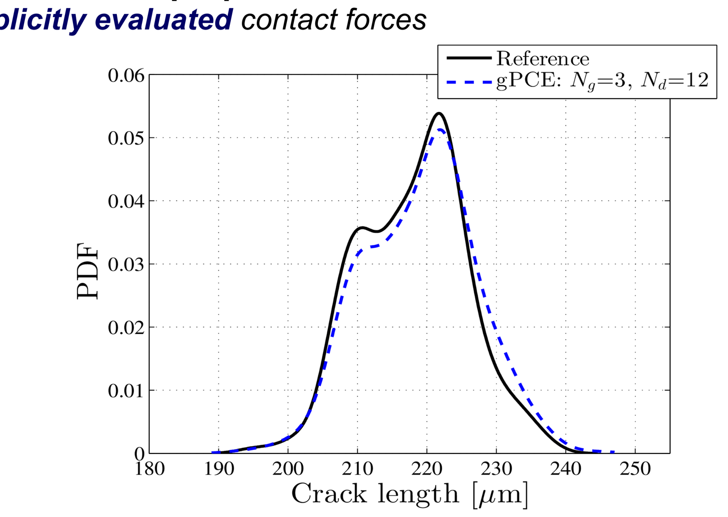
- **Comparison between direct MCS and stochastic model-based methods**
  - The **stochastic model-based method** can **predict the nominate properties** of the crack length distribution.



*The **explicitly evaluated** contact forces*

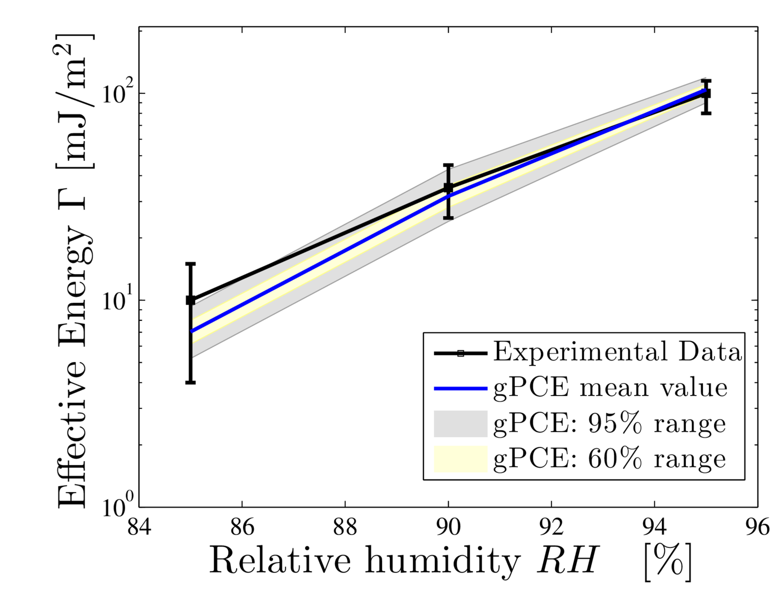


*The **generated** contact forces using the stochastic model*



*The distribution of **crack length** obtained from the direct MCS and stochastic model-based multiscale method. Relative humidity level 85%*

- **Comparison between numerical prediction and experimental data [3]**
  - The **stochastic model-based method** can **predict the experimental results** with **high accuracy**.



*The comparison of the **apparent adhesive energies** predicted by stochastic model and the experimental data [3]. Relative humidity level: 85%, 90%, 95%.*

- **Computational effectiveness. Time** to evaluate 1 realization in one CPU:
  - Direct MCS: ***~16 hours;*** Stochastic model-based method: ***~ 5 minutes.***

Conclusions

- **A novel stochastic multiscale method** to predict the probabilistic behaviors of micro structures involving adhesive contacts is developed.
- The model is **computationally effective**.
- The model is validated by a **comparison with experimental data.**

References

[1] T.-V. Hoang et *al.*, Tribology International, 2016 (submitted).

[2] T.-V. Hoang et *al.*, Journal of Computational and Applied Mathematics 2015.

[3] F. W. Delrio et *al.*, In Scanning Probe Microscopy in Nanoscience and Nanotechnology 3, 2013.

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