SAND2006-6576C

Modeling and Input Optimization Under Uncertainty for a Collection of RF MEMS Devices.

Matt Allen, Rich Field & Jordan Massad

Sandia National Laboratories

Albuquerque, NM

2006 ASME International Mechanical Engineering Congress and Exposition

Chicago, IL

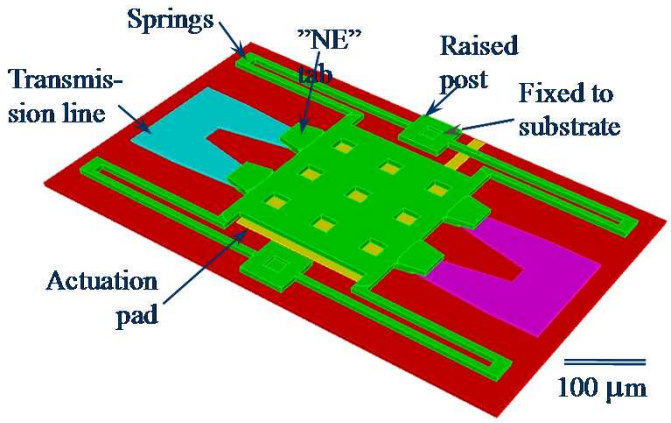
November 2006

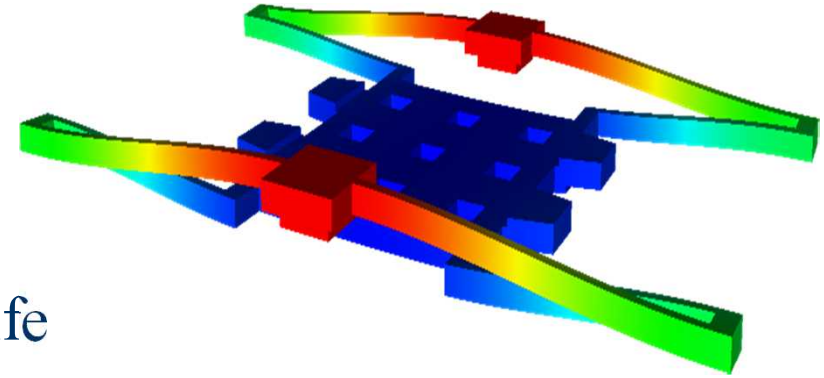
Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Sandia National Laboratories

Introduction

- There has been significant interest in RF MEMS switches because they can potentially provide:
  - very low power consumption
  - high isolation
  - excellent linearity
  - contained in a compact package
- On significant challenge is obtaining the high reliability required.
  - Previous studies have observed orders of magnitude increase in life when the impact velocity of the switches is reduced.





Sandia National Laboratories

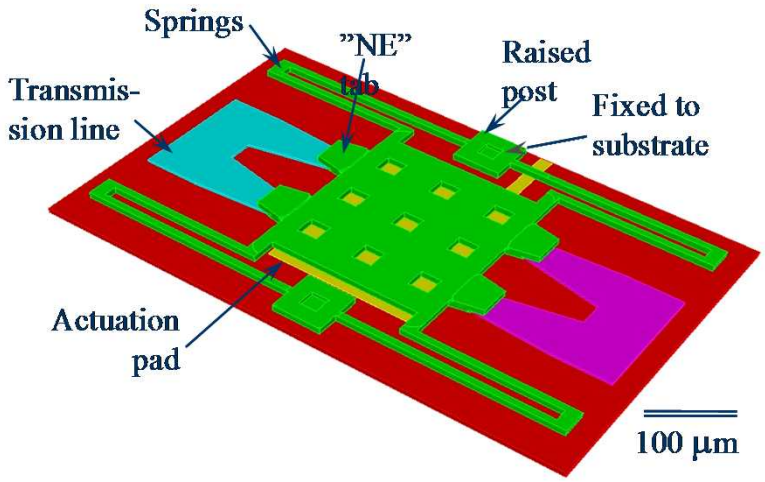
Outline

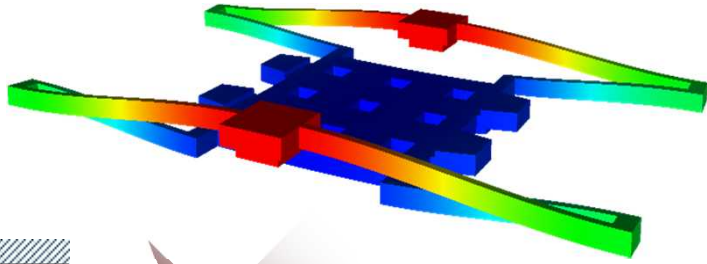
- Switch design and uncertainty model

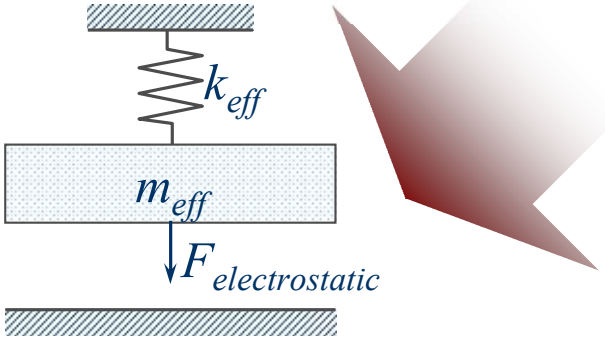
- Unshaped waveform
- Deterministic optimization
- Optimization Under Uncertainty (OUU)
  - Waveform for current design OUU
  - Effect of a design change and OUU
  - Effect of process improvement and OUU
- Conclusions
- Wild cheering and applause

Switch Design

- RF Switch consists of a stiff plate suspended by four folded leaf springs.
- A voltage is applied to a pad under the plate resulting in an electrostatic force that closes the switch.
- The switch is well approximated by a single-degree of freedom model.
  - The input is shaped to limit excitation to higher modes to assure that this assumption is valid.

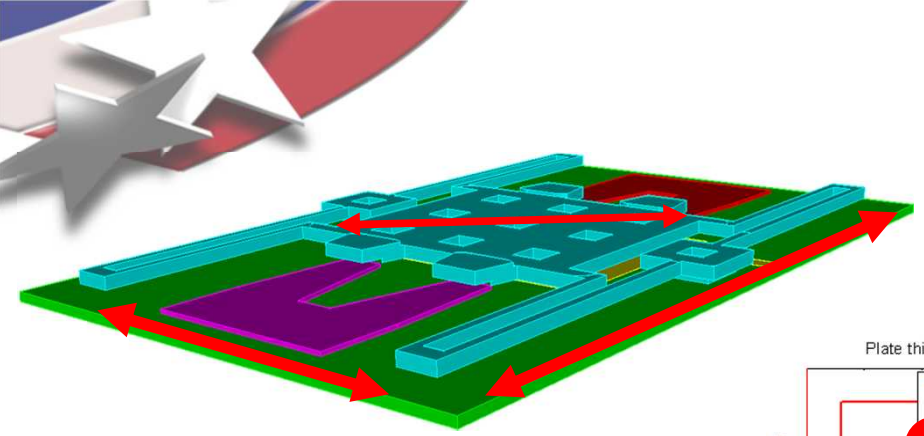


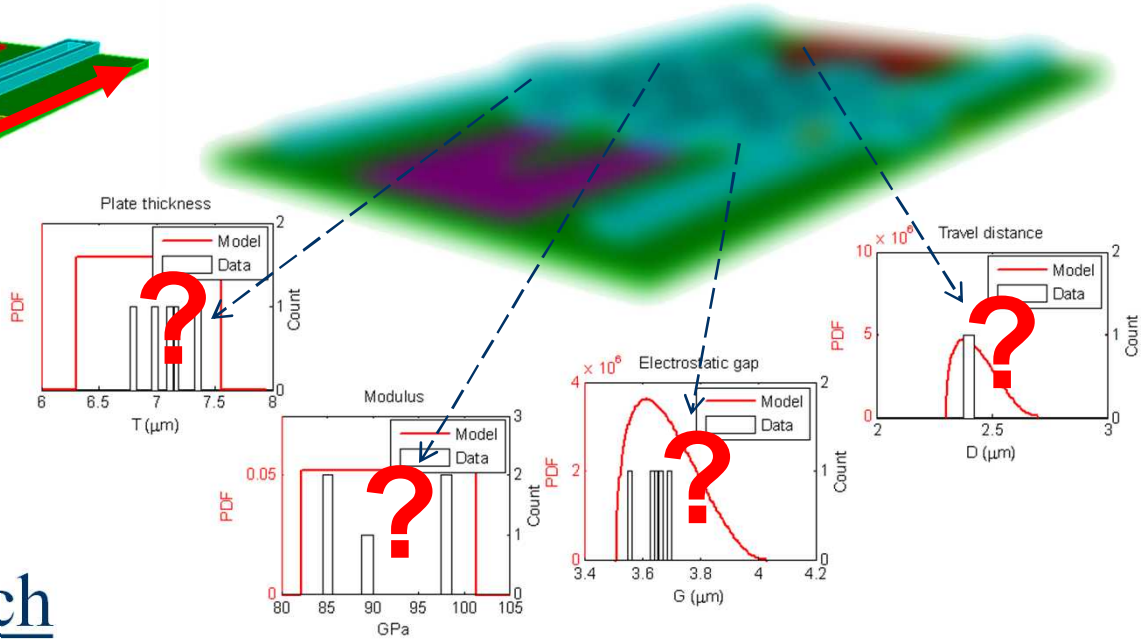




SDOF Model

Sandia National Laboratories





Deterministic Approach

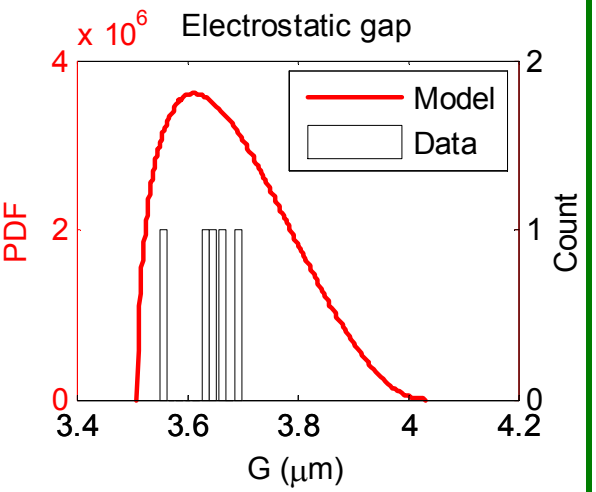
- Variation in switch parameters is ignored.
- Waveform designed semi-analytically to satisfy the switch with average parameters.
- Succeeds only if:
  - The parameters of the switches don't vary too much or
  - If the optimum is insensitive to variation.

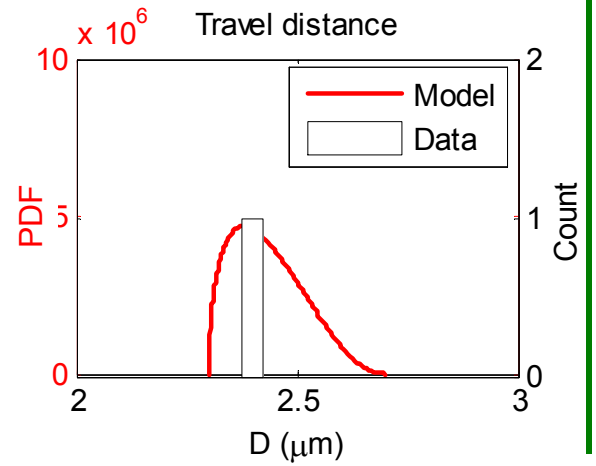
OUU Approach

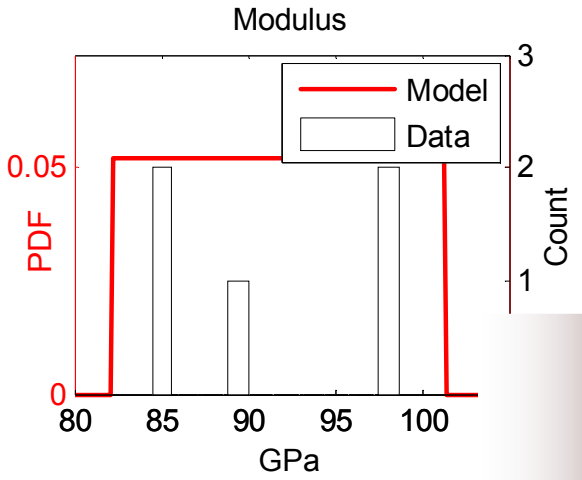
- Random variation in switch parameters described by probability density functions (PDFs).
- Waveform optimized numerically to minimize impact velocity over the ensemble of switches.

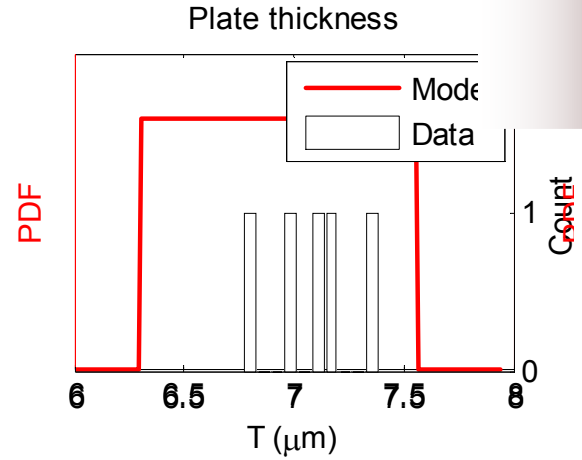
Sandia National Laboratories

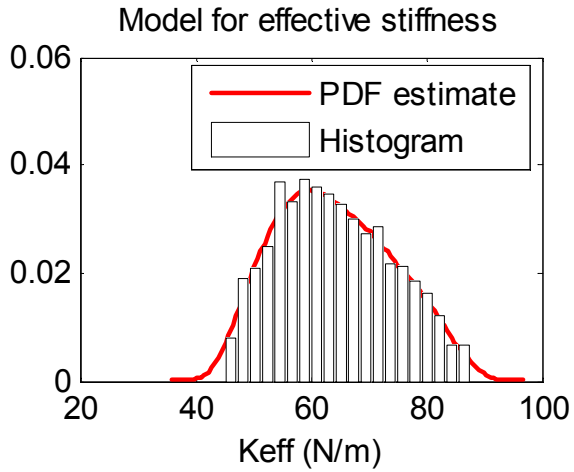
Uncertainty Model

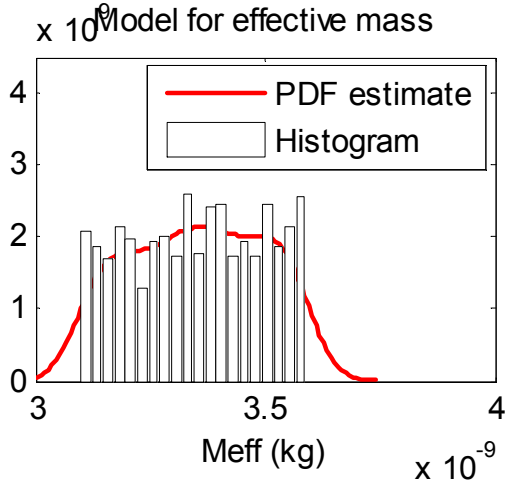








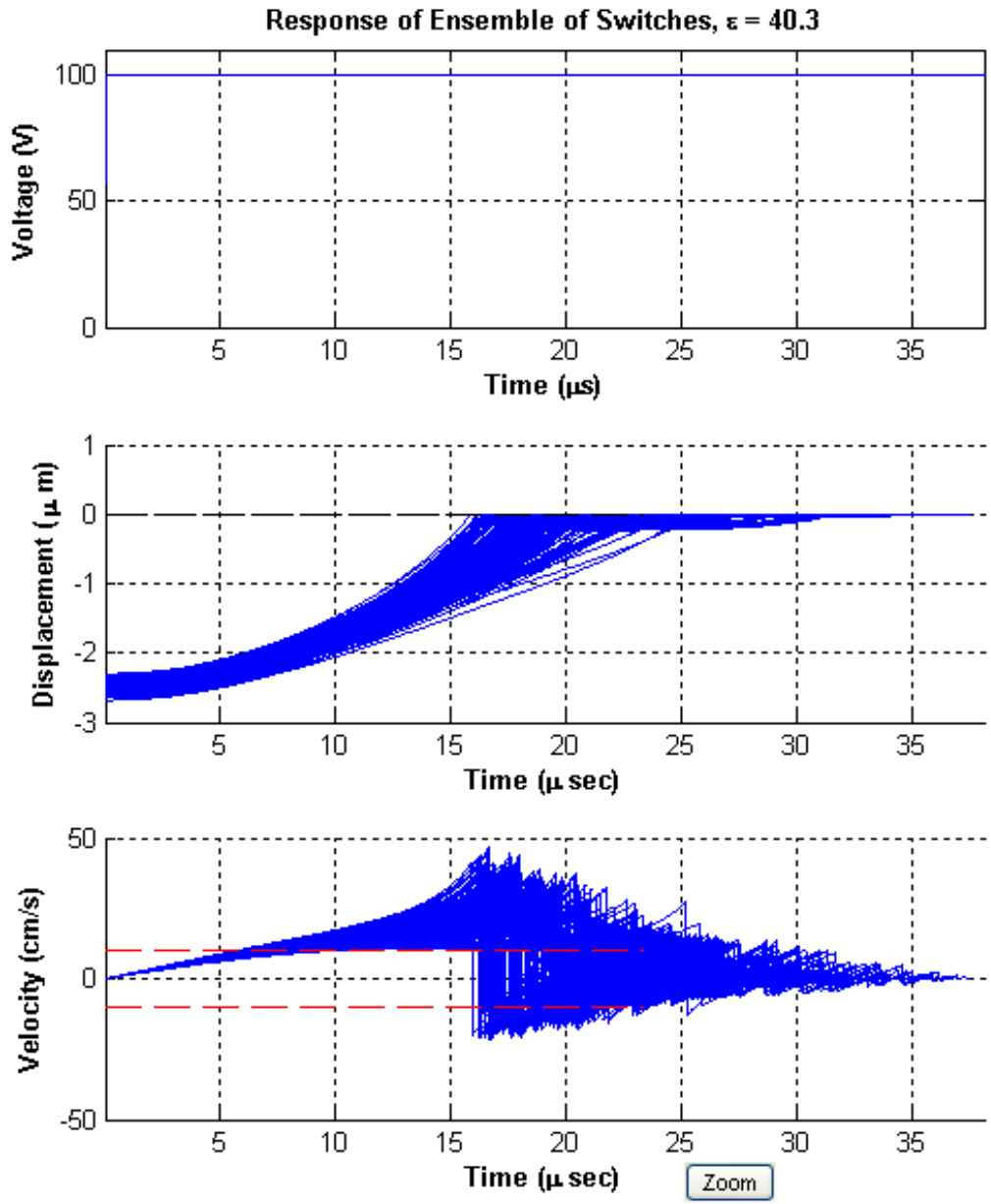


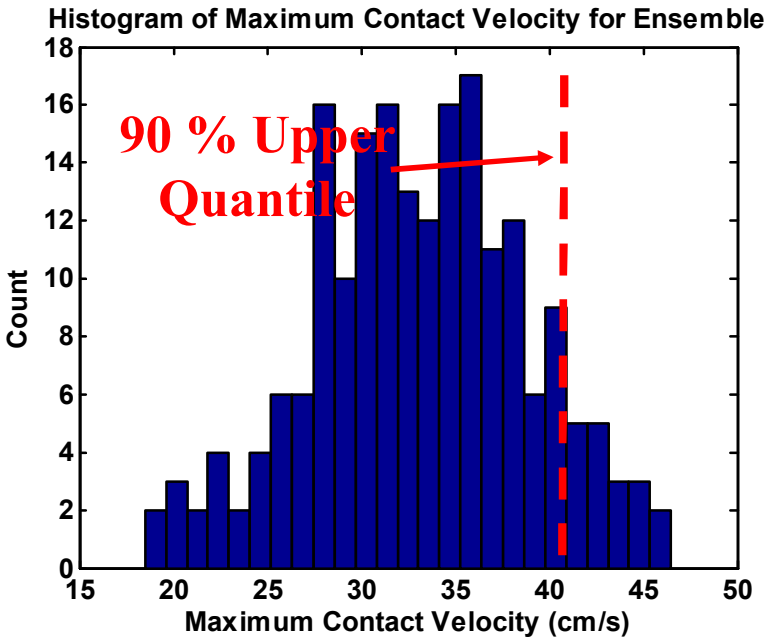


- Plate thickness, electrostatic gap, travel distance and elastic modulus were measured and fit to uniform and Beta Probability Density Functions (PDFs).
  - Expert opinion was used to augment the data since few samples were available.
  - Modulus and Thickness were used to deduce effective mass and stiffness.

Sandia National Laboratories

Response without Input Shaping

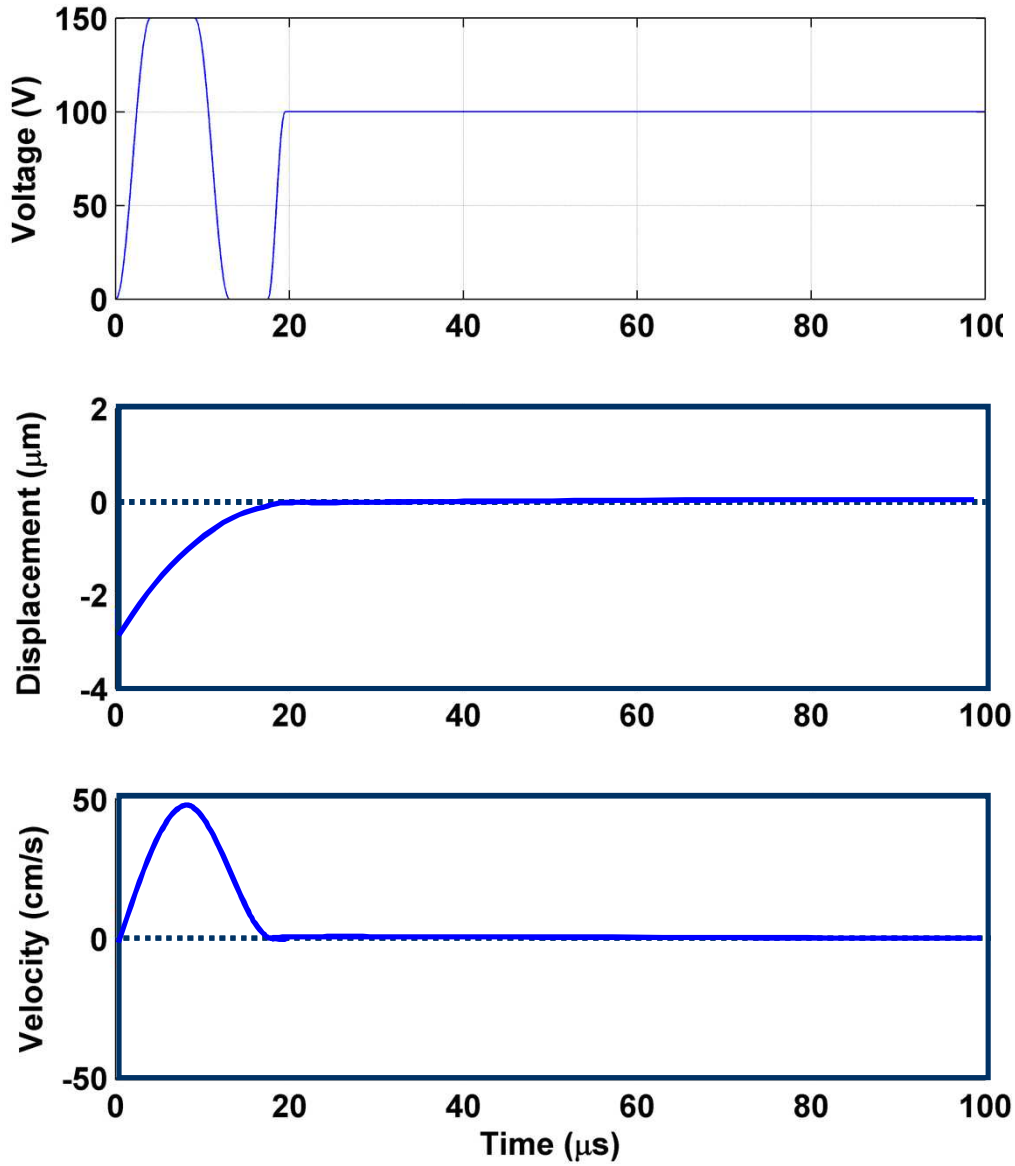


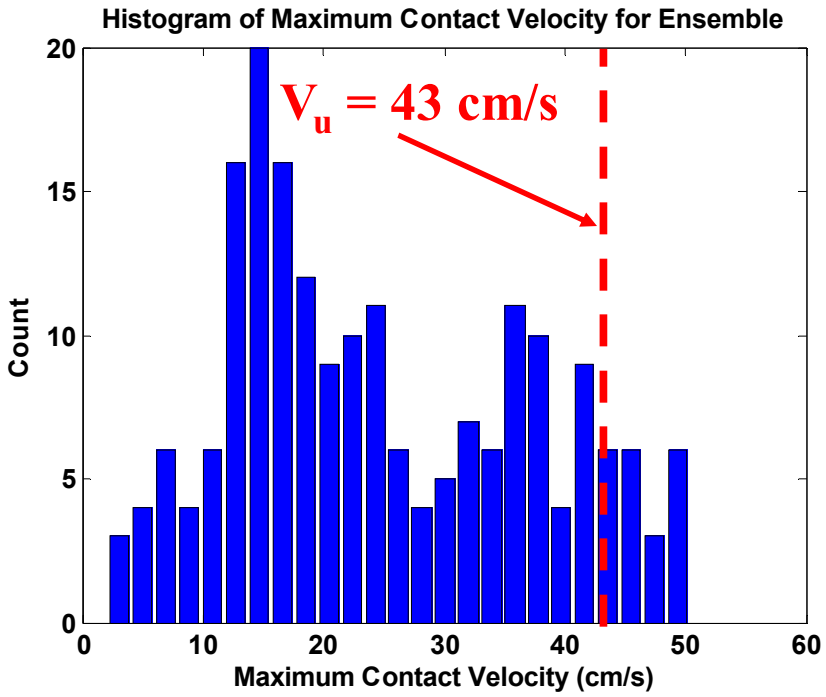


- 90% of the switches experience maximum contact velocities below 40.3 cm/s

Sandia National Laboratories

Deterministic Waveform Design

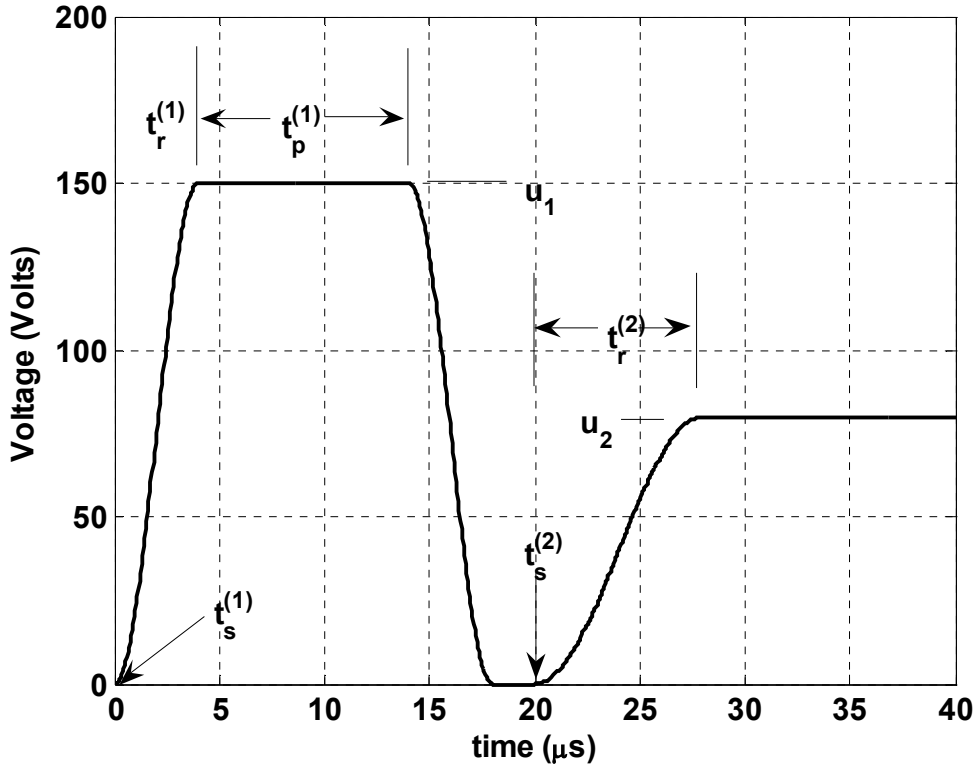




- A waveform that is optimum in a deterministic sense gives higher contact velocities than an unshaped waveform when applied to the ensemble of switches.

Sandia National Laboratories

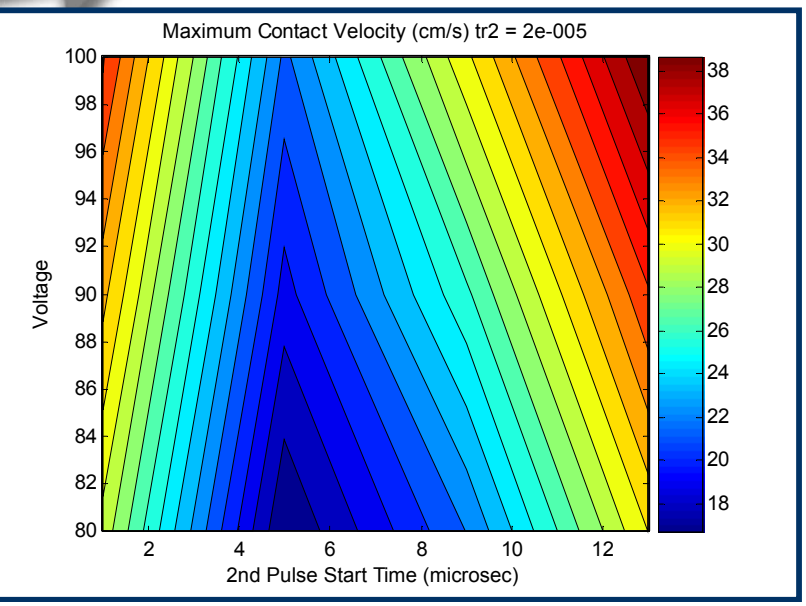
Optimization Objective & Strategy

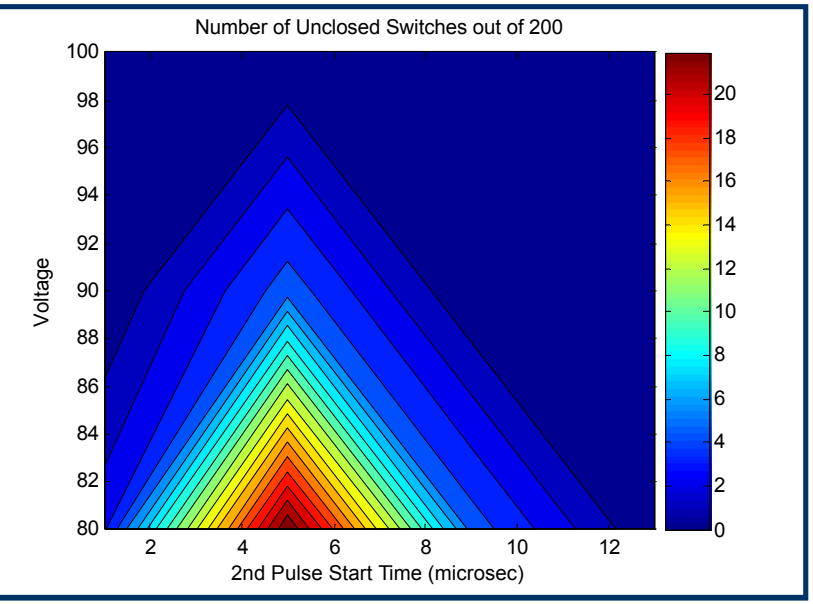


- Optimization Objective:
  - $g(t_s^1,\ldots) = v_u + c_{nc} * p_{nc}$
    - 90% of the switches experience contact velocities lower than v_u
      - (i.e. $P(V_{max} > v_u) = 0.10$)
    - p_{nc} is the probability that a switch doesn't close in 250 μs
    - c_{nc} is a constant to weight the relative importance of the two

- Optimization Strategy:
  - Set $u_2 = 0$ and adjust $t_p^{(1)}$ (duration of first pulse) until the maximum contact velocity for the ensemble of 200 switches is ~10cm/s.
  - Use exhaustive search to find starting values for $t_s^{(2)}$ (start time of second pulse), $t_r^{(2)}$ (rise time of second pulse) and u_2 (maximum voltage of second pulse).
  - Refine using Nelder-Mead Simplex algorithm.

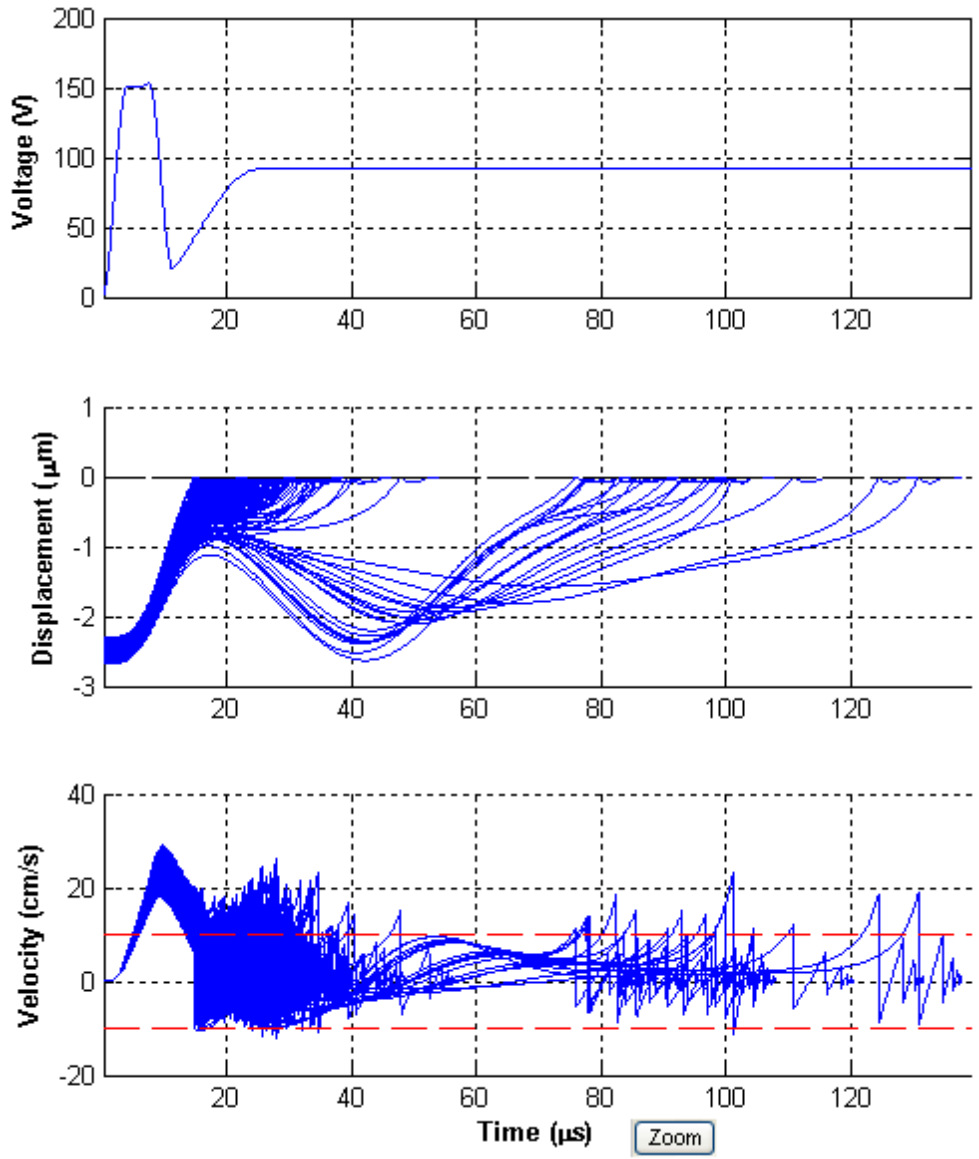
Optimization Strategy

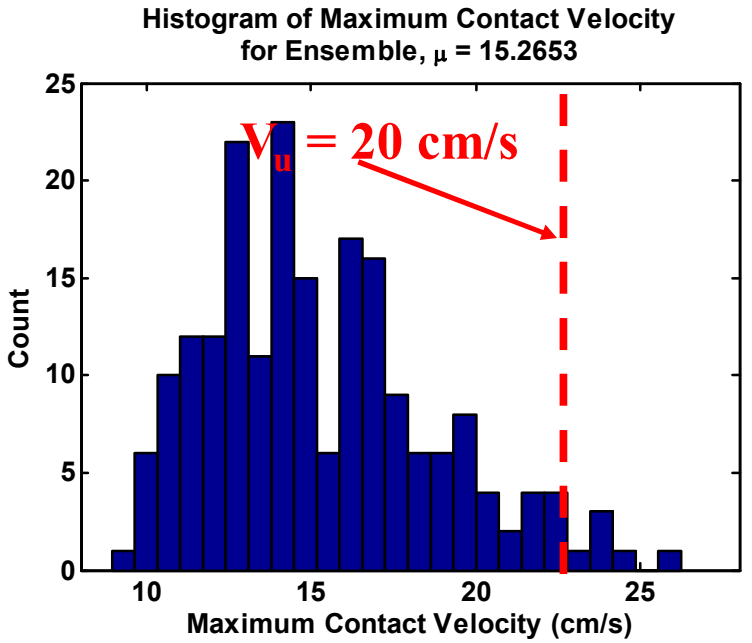




- Comments:
  - Exhaustive search used to find starting values for Nelder-Mead.
  - Nelder-Mead Simplex used to refine initial estimates, typically resulting in a 1 cm/s reduction in the maximum contact velocity from that found by exhaustive search.
  - Also attempted using the DIRECT (global) optimization algorithm, yet many iterations were required to obtain reasonable results.

OUU Waveform Design



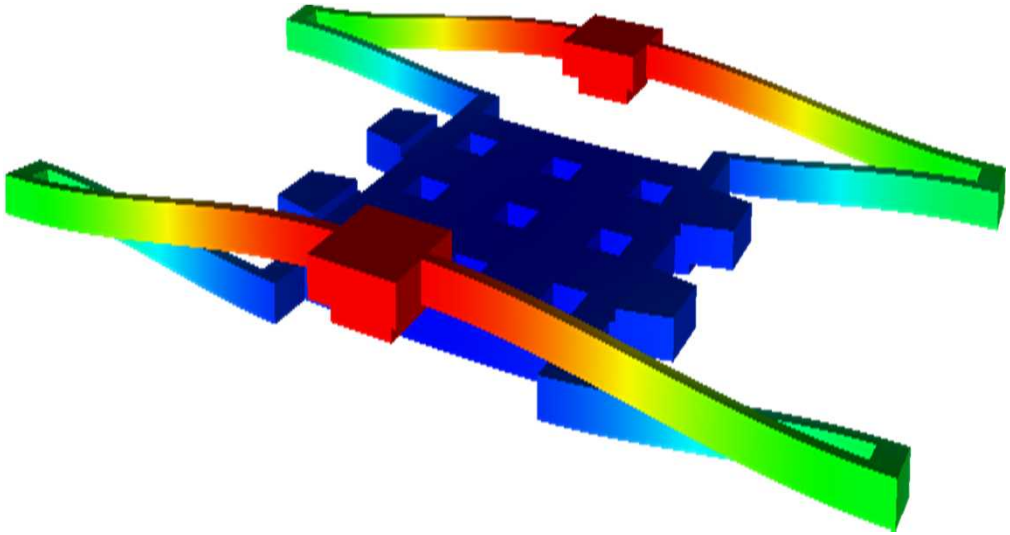


- Results:
  - 90% have maximum contact velocities below 19.7 cm/s
  - The mean maximum contact velocity is 15.3 cm/s
  - These represent improvements of more than 50% compared to the unshaped waveform or the deterministically designed waveform.
- None of the switches have a contact velocity near zero.

Sandia National Laboratories

Design Change

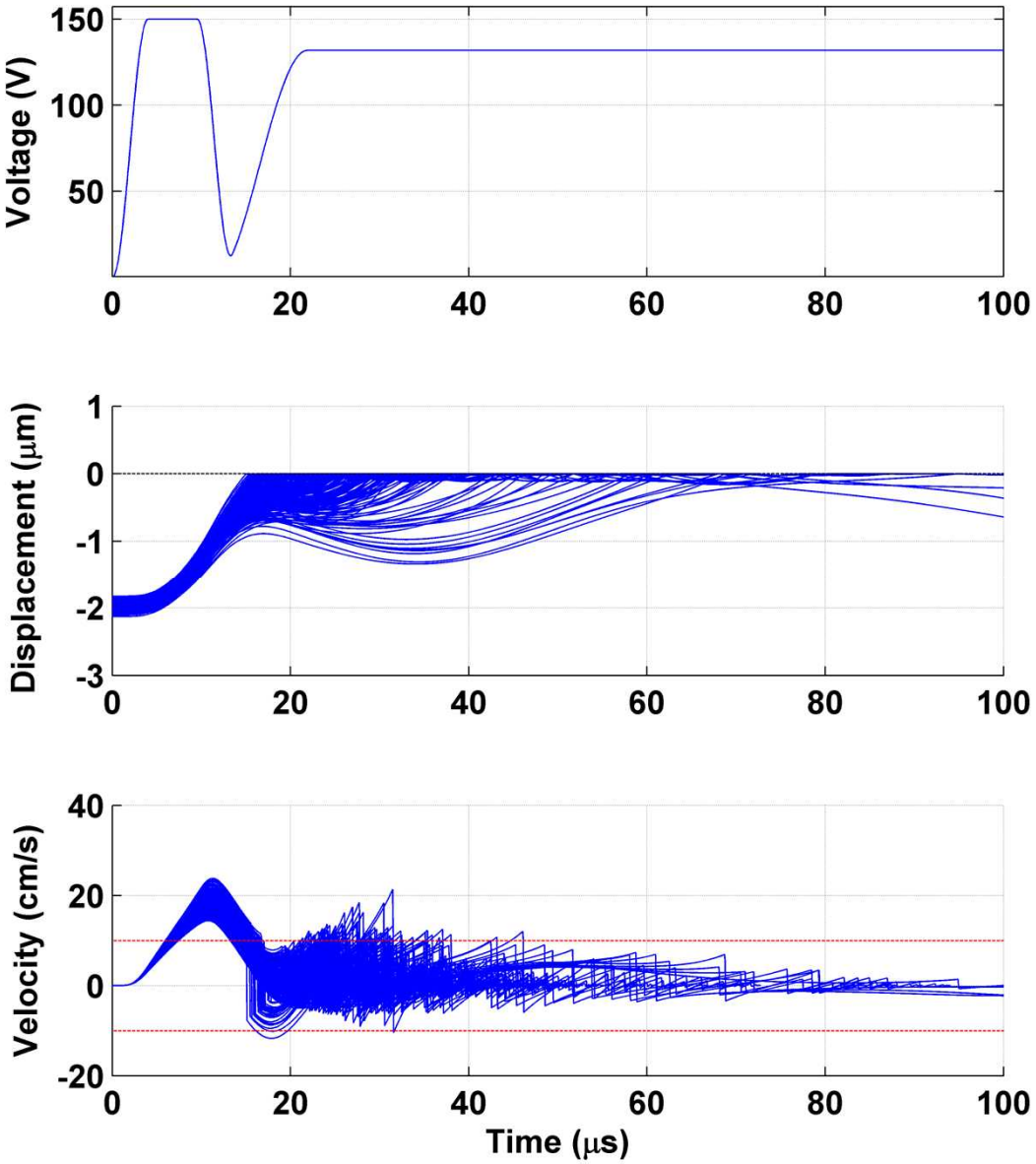
- Electrostatic force varies with the inverse square of the electrostatic gap (G) minus the switch displacement (X).
- The displacement must be less than the travel distance (D).
- The system is unstable for:
  - X > G/3.
- Currently:
  - 0.59 · D/G · 0.75
- The design was modified to reduce this ratio resulting in
  - 0.41 · D/G · 0.52.
- This design does not venture as far into the unstable region as the previous did.

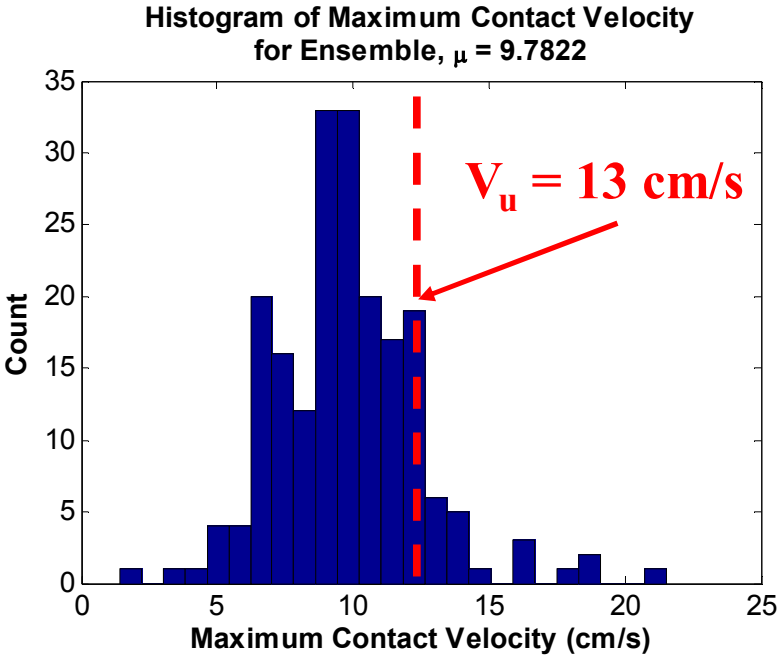


$$F_{electrostatic} = \frac{\alpha u^2}{(G-X)^2}$$

$$X \leq D$$

Design Change and OUU



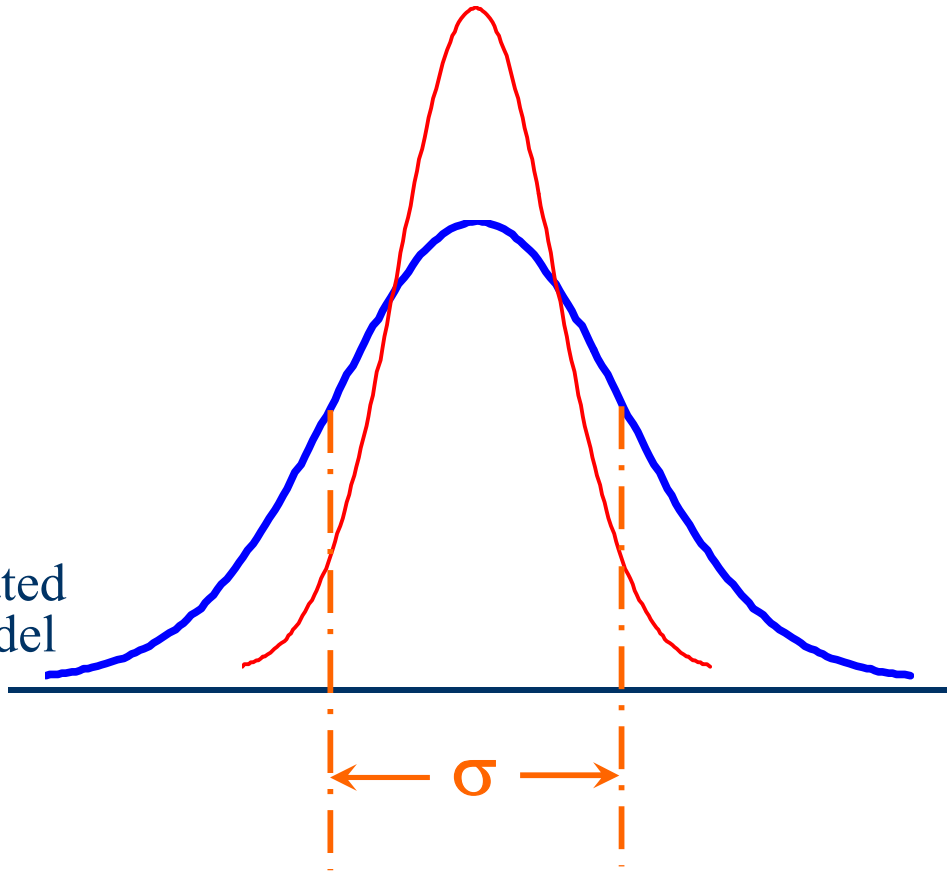


- 35 % reduction in upper and mean contact velocities.
  - Upper 12.5 cm/s from 19.7 cm/s
  - Mean 9.8 cm/s from 15.3 cm/s

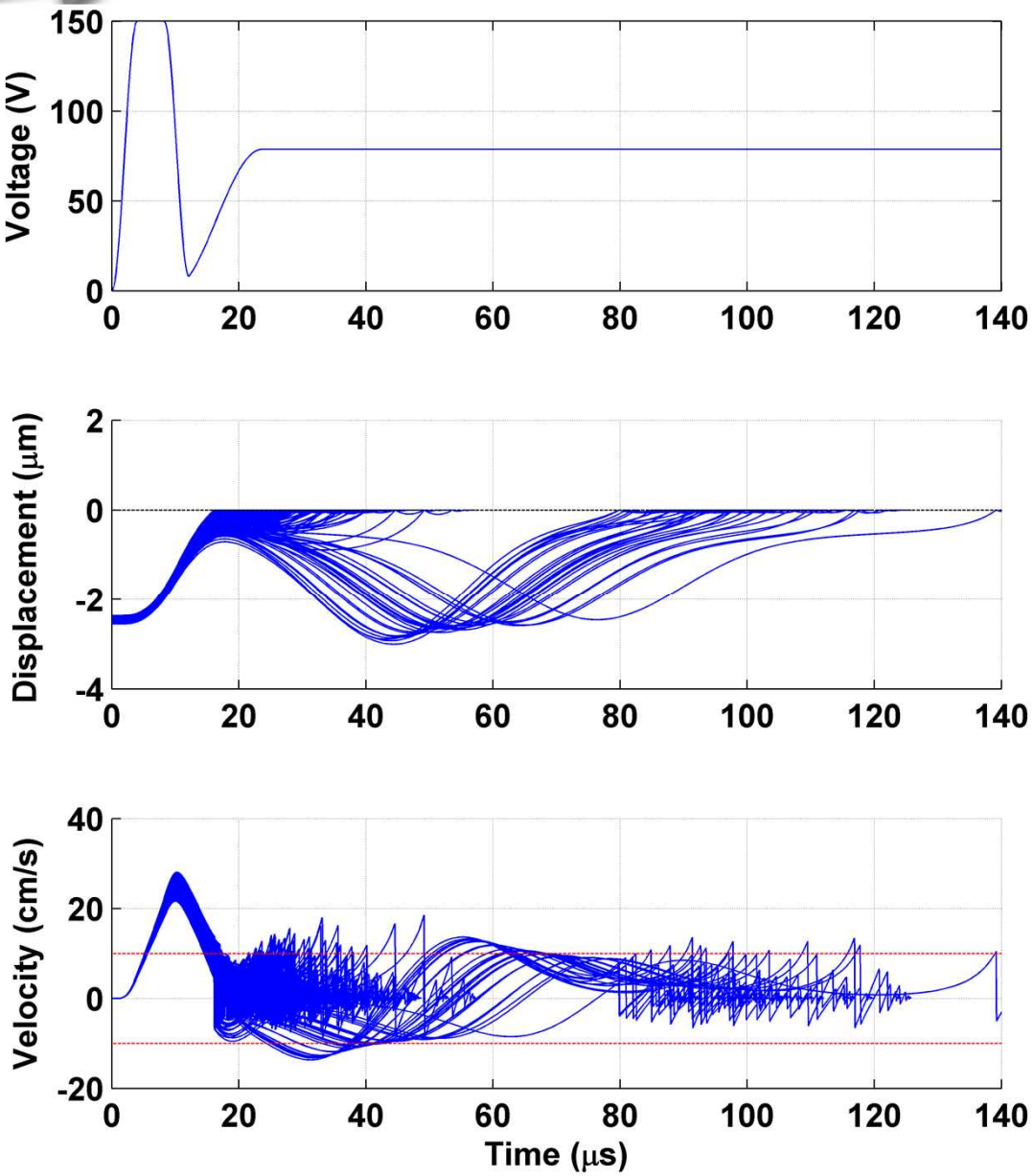
Sandia National Laboratories

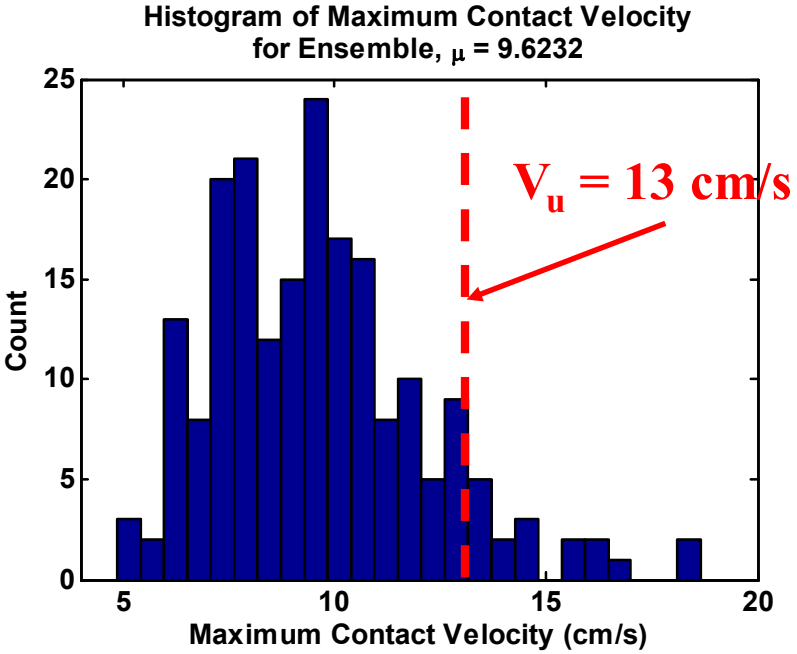
Process Improvement

- How much would the performance improve if the process repeatability were improved by 50%?
  - Coefficient of Variation of:
    - Gap Distance
    - Travel Distance
    - Thickness
  - were decreased by 50%. (COV = standard deviation / mean).
  - Optimization procedure was repeated with this modified uncertainty model for the switch.
- This level of improvement may not be feasible, but this type of analysis can provide motivation for allocating resources to process improvement.



Process Improvement and OUU

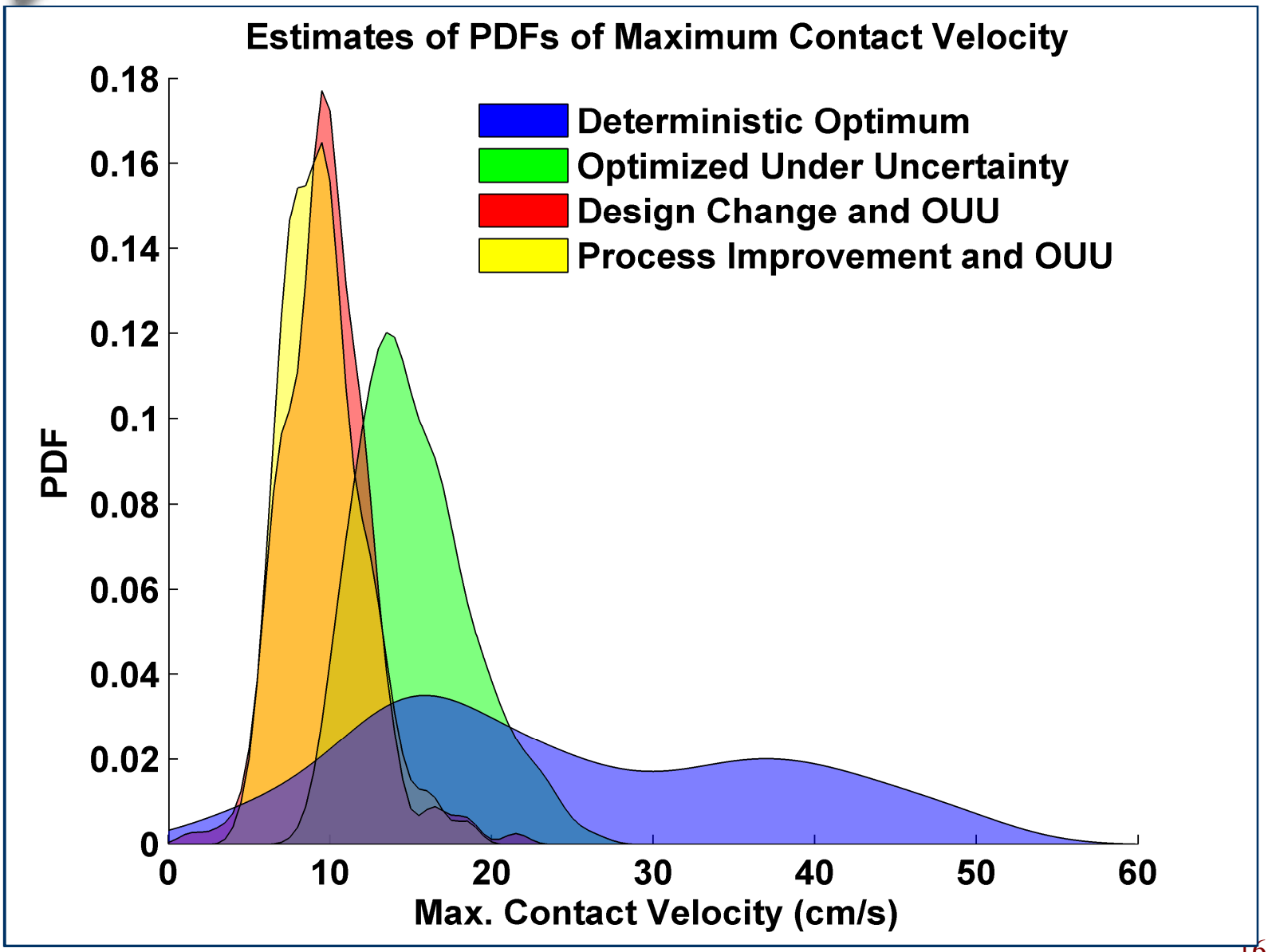




- Simulated the effect of process improvement:
  - Reduced the COV of gap, travel and thickness by 50%
- >35% reduction in upper and mean contact velocities
  - Upper 12.8 cm/s vs 19.7 cm/s
  - Mean 9.6 cm/s vs. 15.3 cm/s

Sandia National Laboratories

Summary



Sandia National Laboratories

Conclusions

- Shaped waveforms can reduce the impact velocity that an ensemble of switches experiences.
- The contact velocity was reduced by 50% using the waveform that was optimized under uncertainty.
- Further reductions of 35% were demonstrated after modifying the switch design or reducing process variability. (Net reduction of 70%)
- Uncertainty must be accounted for when designing shaped waveforms.
  - A waveform that was optimum for the average switch actually increased the impact velocity when applied to the ensemble of switches.