Modeling Component Failure Rates Utilizing Sensor-Based Degradation Data

Vaibhav Yadav, PhD
Vivek Agarwal, PhD
Andrei V. Gribok, PhD
Curtis L. Smith, PhD

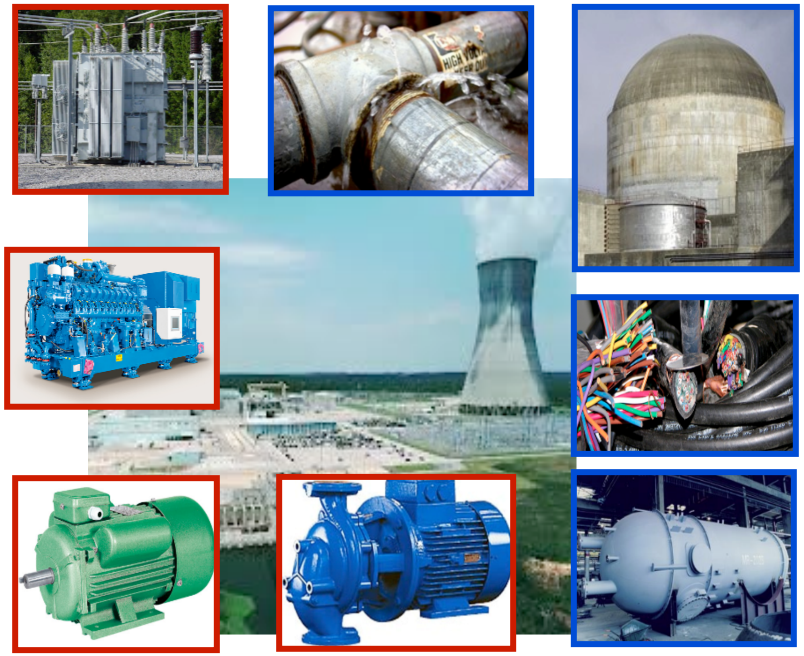
Nuclear Safety and Regulatory Research Division

Probabilistic Safety Assessment and Management
PSAM 14, September 2018, Los Angeles, CA

Aging and Degradation in Risk Analysis

Aging and Degradation in Risk Analysis

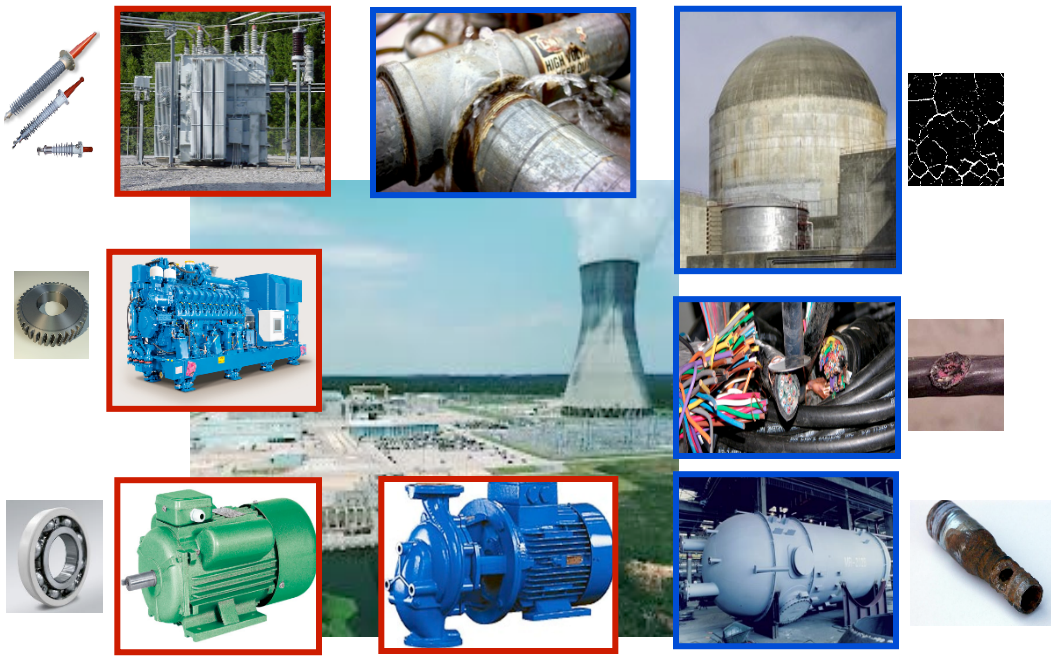
Aging and Degradation in Risk Analysis



Active SSCs

Passive SSCs

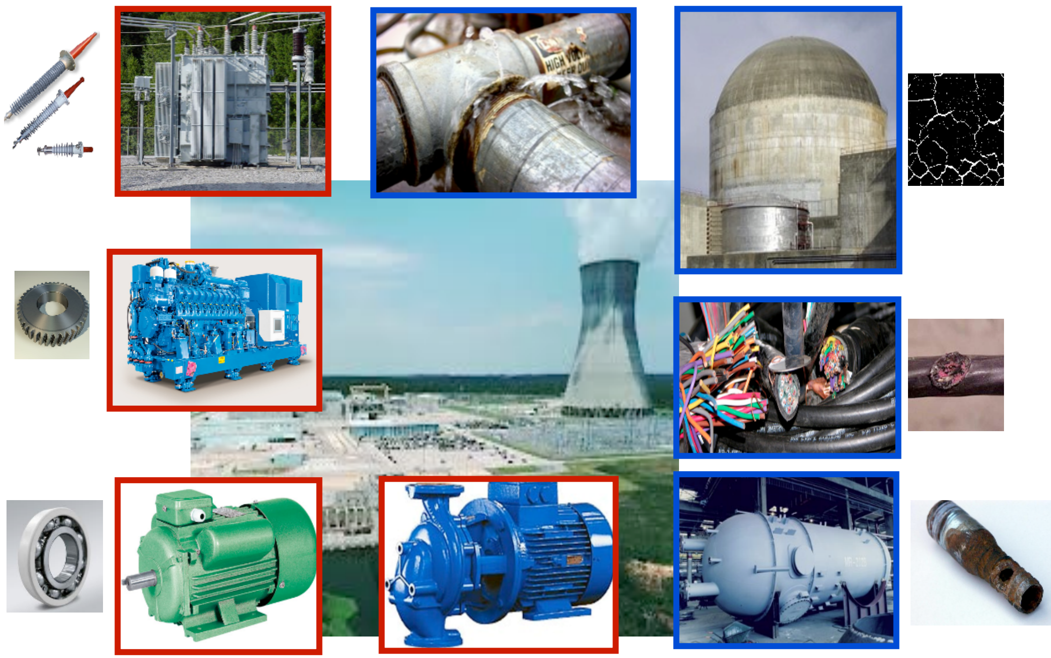
Aging and Degradation in Risk Analysis



Active SSCs

Passive SSCs

Aging and Degradation in Risk Analysis



Active SSCs **Passive SSCs**

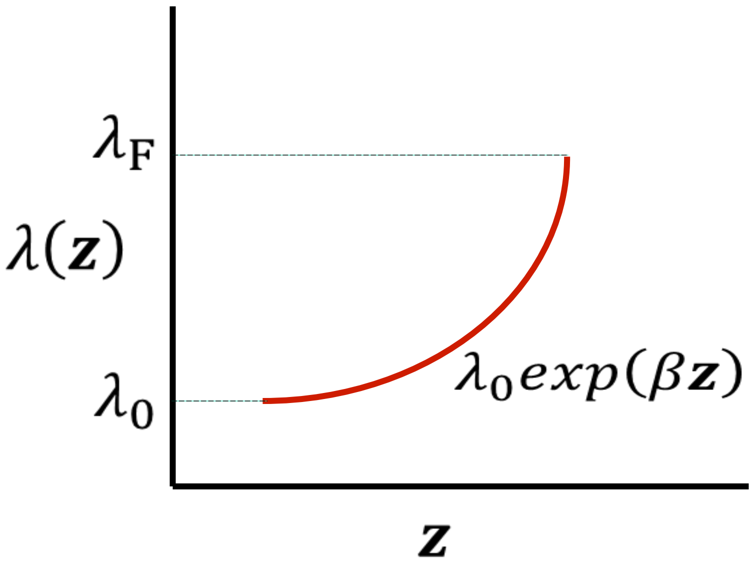
Failure Rate Model

$$\lambda(\mathbf{z}) = \lambda_0 exp(\beta \mathbf{z})$$

- $\mathbf{z}$ is a matrix of performance data of dimension $M \times N$. M is the Test # and N is the performance data
  - *Vibration, temperature, flow-rate, pressure, loading etc.*
- λ_0 is the baseline failure rate
- β is an unknown parameter

Failure Rate Model

- λ_{F} be the failure rate when the component failed
- λ_{F} is obtained from a population of failed components
- $\lambda \sim$ Gamma (α, β) prior distribution
- N failed components with time to failure $t_1, t_2 \ldots, t_N$
- Updating distribution of λ using Bayesian inference
- $\lambda_{\mathrm{F}} \sim Gamma\left(\alpha + N, \beta + \sum_{i=1}^{N} t_i\right)$



Motor Testing*

- Ten three phase 5-HP, 3600 rpm motors
- Each motor was run to failure while underdoing accelerated degradation on a weekly basis
- A cyclic thermal aging process designed to induce accelerated insulation breakdown and corrosion within the motors
    1. Heated for three days in an oven.
    2. Placed in a moisture testing bed with high humidity for further degradation
    3. Allowed to cool for a few hours
    4. Placed in the second heating cycle for three additional days
    5. Placed on a test bed and run for one hour
- Each motor was mounted on a test bed, connected to a generator, and instrumented with a data collection system to collect various signals

*Barbieri, Federico, J. Wesley Hines, Michael Sharp, and Mauro Venturini. "Sensor-Based Degradation Prediction and Prognostics for Remaining Useful Life Estimation: Validation on Experimental Data of Electric Motors." International Journal of Prognostics and Health Management 6 (2015): 1-20.

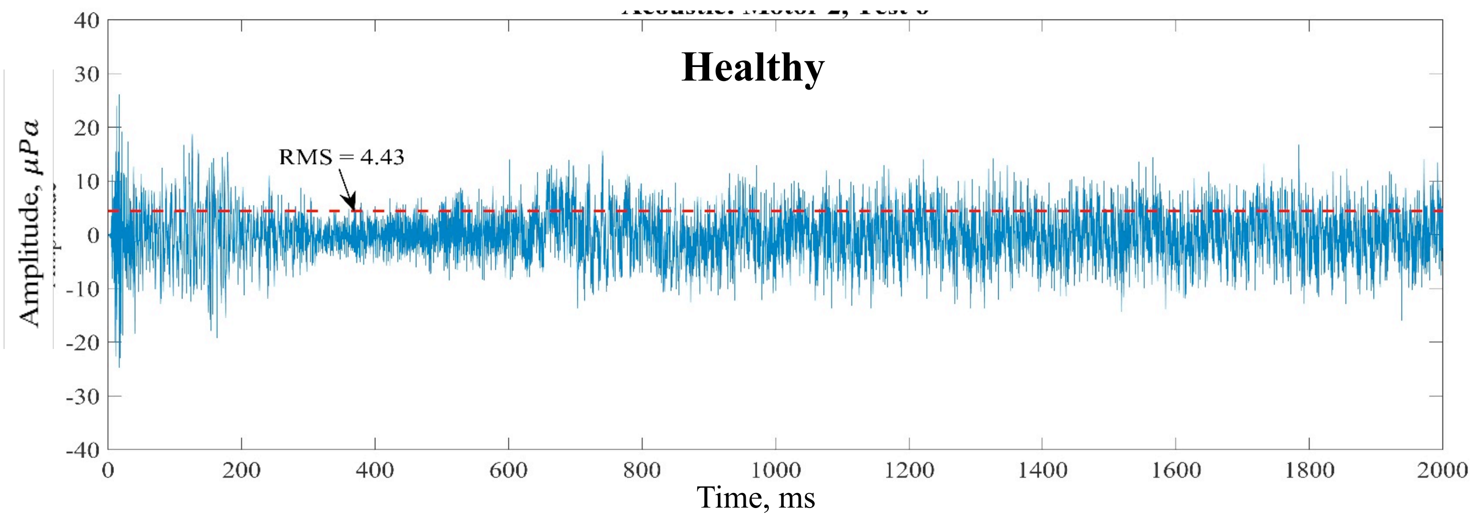
Measurement Data

- Fifteen different parameters were measured for each motor:
  - Input Current and Voltage for each of the three phases (1-6)
  - Phase angle (7)
  - Vibration horizontal and vertical (8-9)
  - Acoustic amplitude (10)
  - Tachometer data (11)
  - Speed in rpm (12)
  - Output current and voltage (13-14)
  - Temperature (15)
- One parameter is used to keep the methodology simple to demonstrate
- The acoustic data was found to be most significant in capturing motor degradation
- A subset of five motors (# 2, 3, 4, 5, and 6) that demonstrated the strongest acoustic signals was used

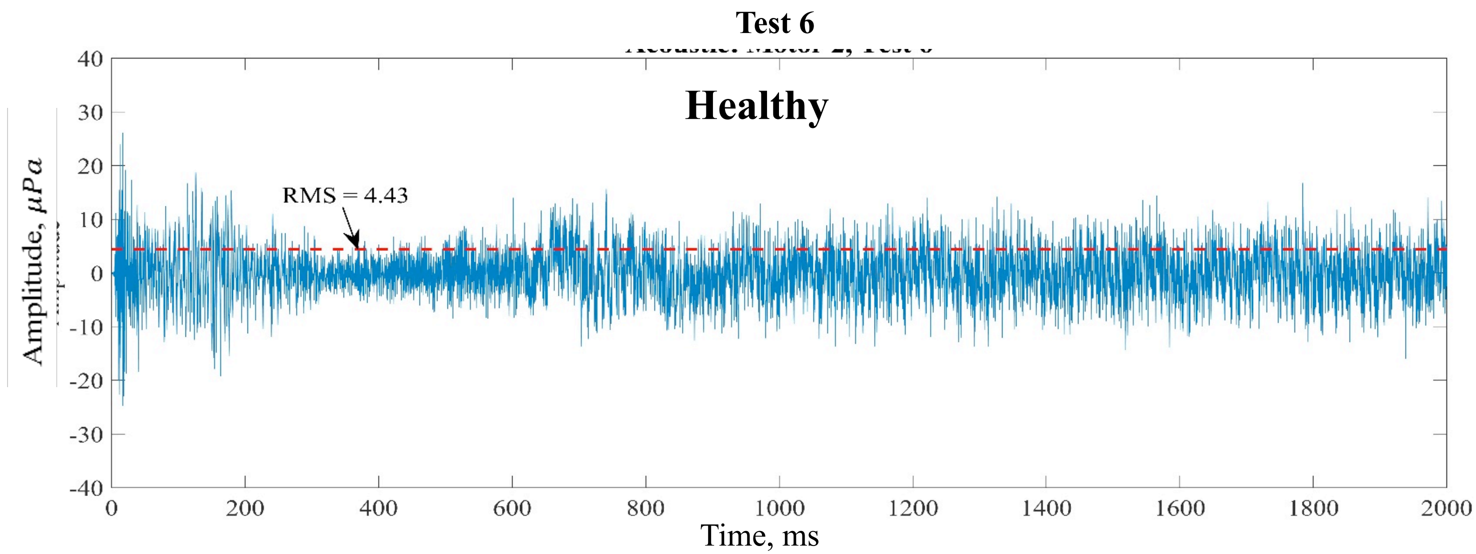
Motor	2	3	4	5	6
Time to Failure (**L**)	150	131	156	133	151

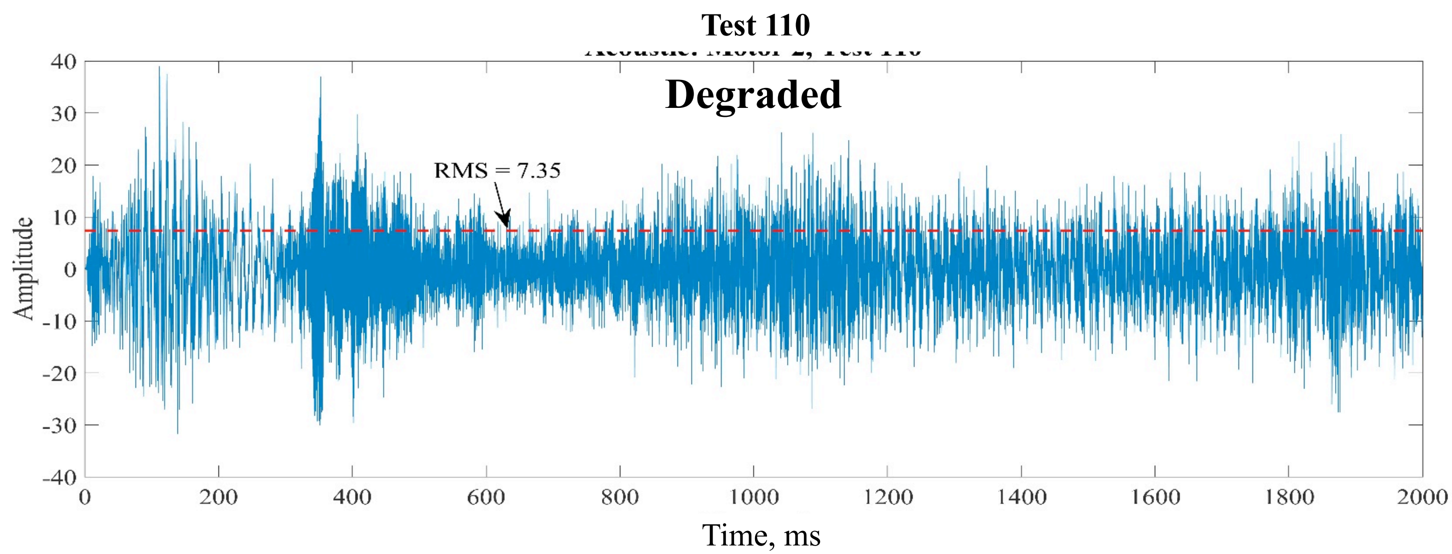
Acoustic Data

Test 6

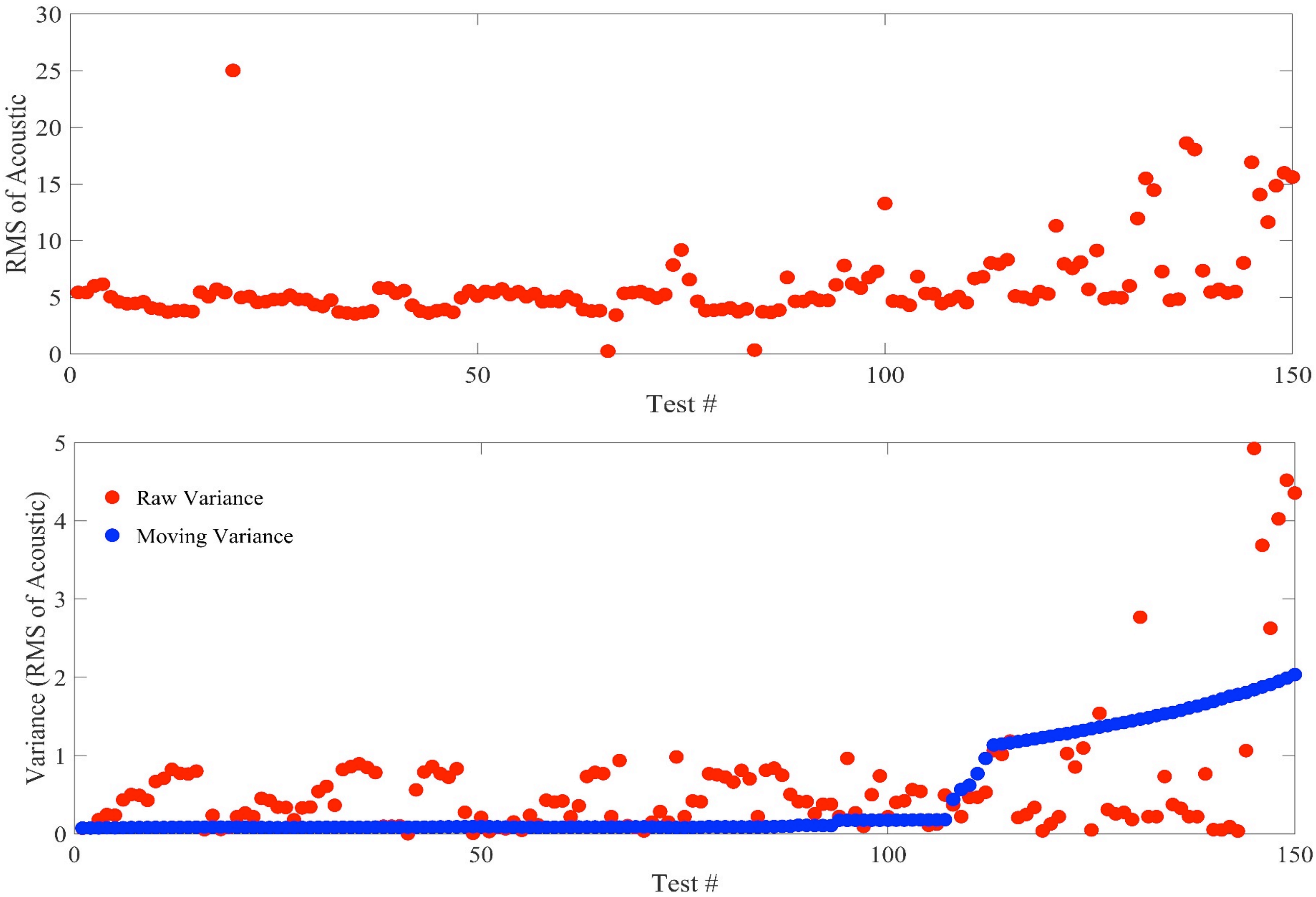


Acoustic Data





Outlier Detection and Smoothing



Window Size for Moving Variance

Window size = 2

Low mean
High standard deviation

Window size = L

High mean
Low standard deviation

Optimum Window Size

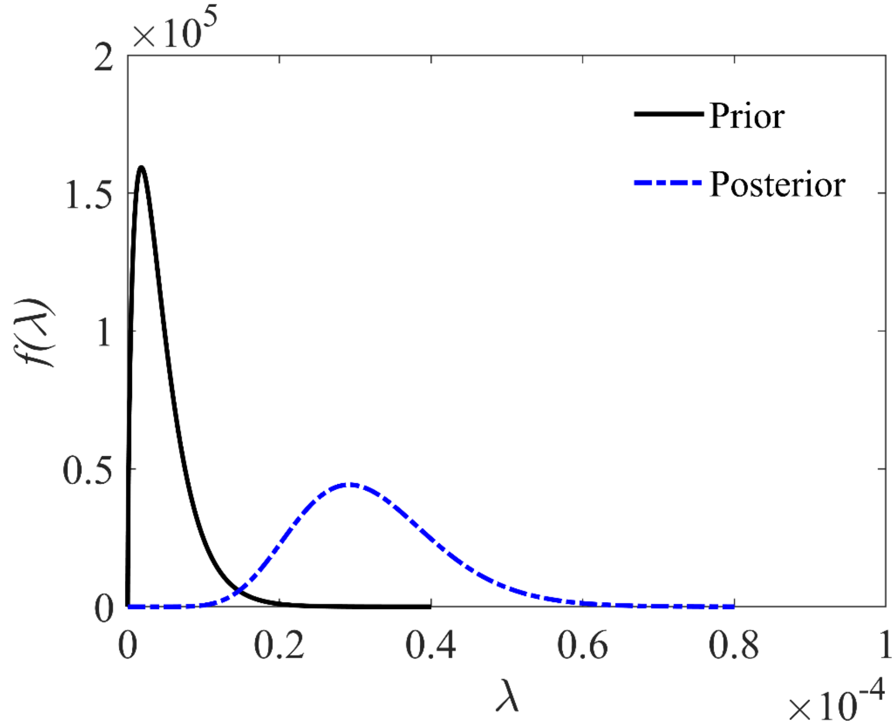
$$\text{Objective function} = \text{ABS}(\text{Mean} - \text{Standard deviation})$$

Moving Variance with Optimum Window Size

Average of optimum window size = 73

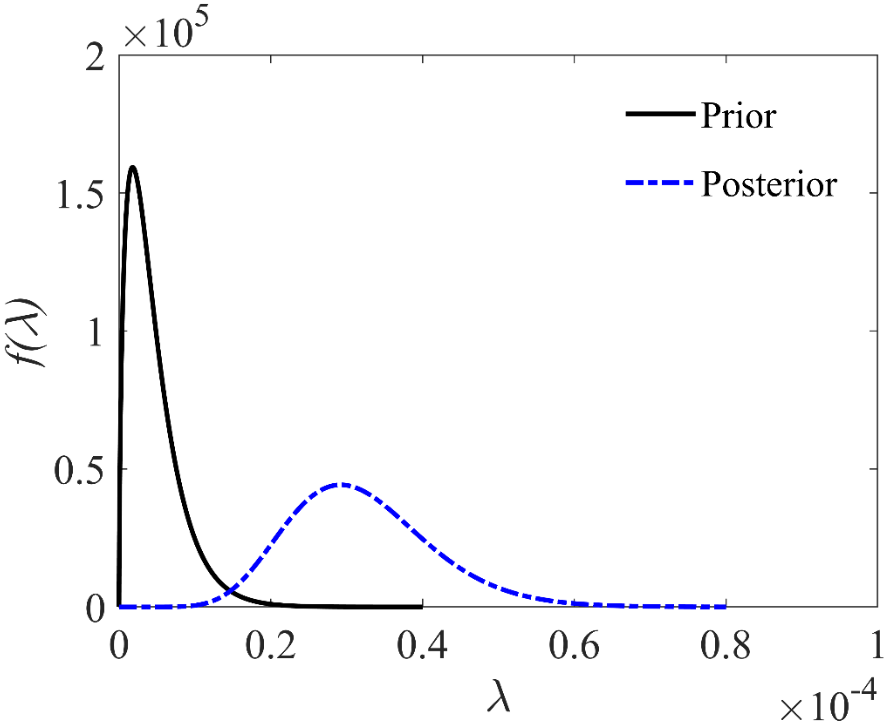
Failure Rate Model

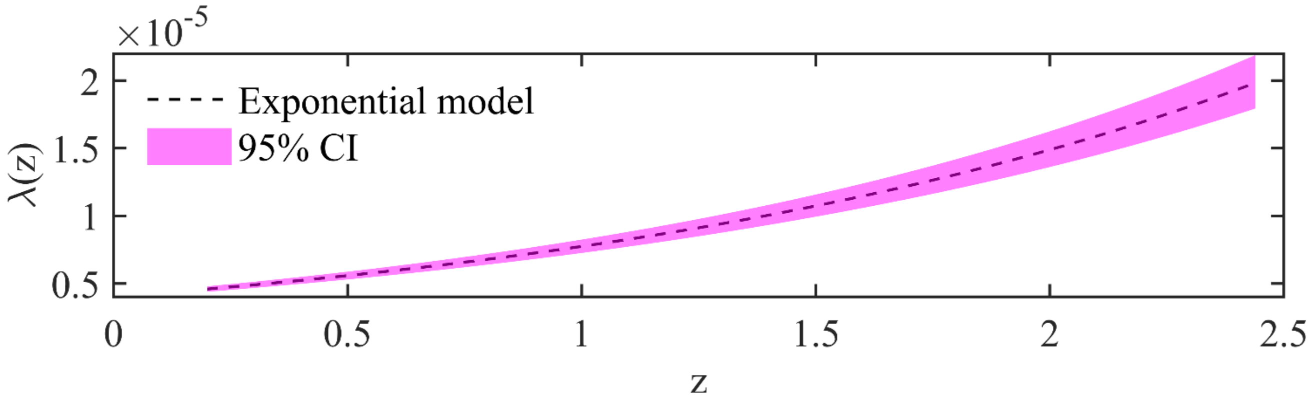
- Mean failure rate λ_0 = $4.54 \times 10^{-6}/hr$ and $\alpha = 1.655$ obtained from NUREG/CR-6928
- t_i = 150, 131, 156, 133, 151 hours, i = 1,…,5
- $\lambda_F \sim Gamma\left(\alpha + 5, \beta + \sum_{i=1}^{5} t_i\right)$
- $\lambda(z) = \begin{cases} \lambda_0 & z < z_{th}, \\ \lambda_0 exp(\beta z) & z \geq z_{th}. \end{cases}$
- z_{th} = 0.2 as onset of degradation



Failure Rate Model

- Mean failure rate $\lambda_0 = 4.54 \times 10^{-6}/hr$ and $\alpha = 1.655$ obtained from NUREG/CR-6928
- $t_i = 150, 131, 156, 133, 151$ hours, $i = 1,\ldots,5$
- $\lambda_F \sim Gamma\left(\alpha + 5, \beta + \sum_{i=1}^{5} t_i\right)$
- $\lambda(z) = \begin{cases} \lambda_0 & z < z_{th}, \\ \lambda_0 exp(\beta z) & z \geq z_{th}. \end{cases}$
- $z_{th} = 0.2$ as onset of degradation





Conclusion and Future Work

- A framework to model failure rates of components as a function of their performance measure is demonstrated
- An exponential model is proposed and is modeled using the failure rate of component in a healthy state
- Failure rate obtained in a failed state from Bayesian inference
- The model is demonstrated using experimental data obtained from an accelerated degradation test
- The failure rate evolution is modeled as a function of moving variance of the RMS value of acoustic amplitude
- The model can be used for estimating the mean failure rate of components under degradation
- Future work entails incorporating multivariate covariates into the exponential model of failure rate, and performing rigorous validation of the proposed model

Acknowledgment

- Work supported through the INL Laboratory Directed Research& Development (LDRD) Program under DOE Idaho Operations Office Contract DE-AC07-05ID14517.
- The University of Tennessee, Knoxville for the motor degradation data