Bistable and Adaptive Piezoelectric Circuitry for Impedance-Based Structural Health Monitoring

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Outline of the Presentation

- Background on Structural Health Monitoring
- Problem Statement and Research Goal
- Impedance Data Enrichment Concept
- Bifurcation-based Sensing Method
- Scholarly Contributions and Impacts
- Proposal for Future Plan

Background: Structural Health Monitoring

Background: Structural Health Monitoring

Boeing 737-700

Ocotillo CA

System Health Management: *Capabilities of a system that preserve the system's ability to function as intended*

➔ Life-safety and economic impact

Diagnosis

Structural Health Monitoring (SHM)

Usage Monitoring

Prognosis

System Health Management

Determine

- condition-based maintenance,
- remaining useful life
- operational plan

- fault detection
- localization
- damage characterization.

Background: Structural Health Monitoring

Vibration-based methods (Farrar et al 2001; Carden and Fanning, 2004)

- **Merit:** Easy to implement, large sensing area
  Identification of damage location and severity
- **Limitation**: Low frequency / not sensitive to small damage

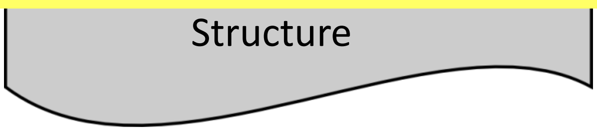
Wave propagation-based methods (Raghavan and Cesnik 2007)

- **Merit**: High frequency / incipient small damage detectable
- **Disadvantage**: Challenges in identifying the severity of damage

Piezoelectric impedance-based methods (Park et al 2003; Wang and Tang 2010)

- Utilize the electromechanical coupling effect of the piezoelectric transducer
- ***Simple implementation***
- ***Damage location / severity identification***
- ***High sensitivity to small damages***

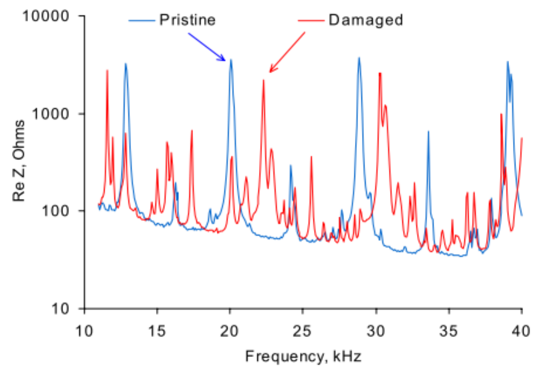
Piezoelectric impedance



Background: Impedance-based Methods

Impedance data-based methods

- **Frequency spectra analysis methods**
  - **Merit**: straightforward implementation
  - **Limitation**: only detection
    non-physical damage index



Zagrai, Giurgiutiu, 2002

Impedance model-based methods

Background: Impedance-based Methods

Impedance data-based methods

- **Frequency spectra analysis methods**
  - **Merit**: straightforward implementation
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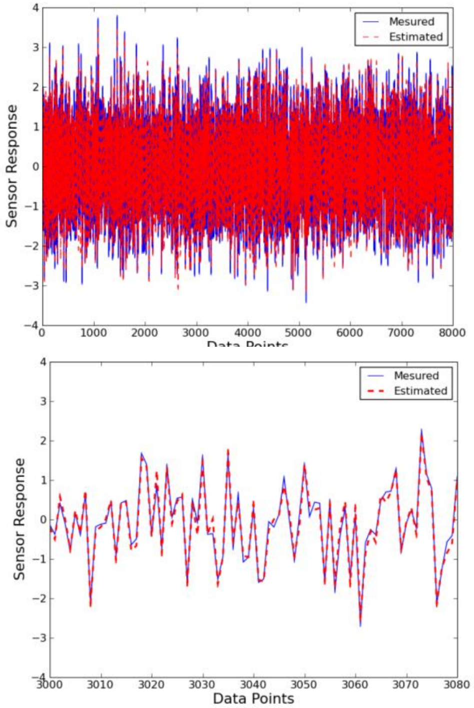
    non-physical damage index
- **Time-series analysis methods**
  - **Merit**: real-time health monitoring
  - **Limitation**: only detection
    phenomenological model



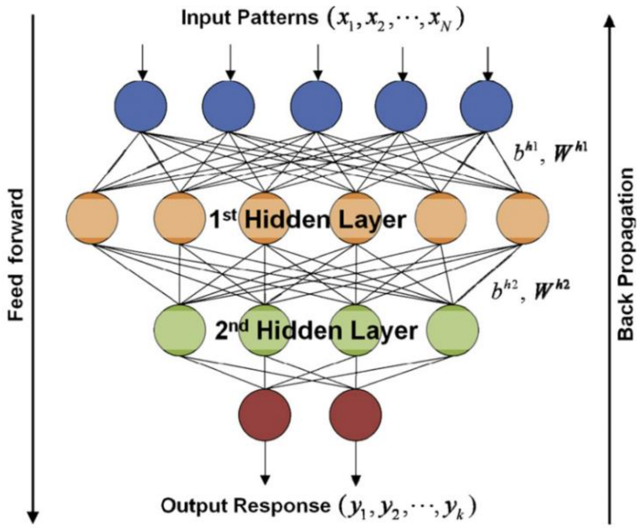
Park et al. 2010

Impedance model-based methods

Background: Impedance-based Methods

Impedance data-based methods

- **Frequency spectra analysis methods**
  - **Merit**: straightforward implementation
  - **Limitation**: only detection
    non-physical damage index
- **Time-series analysis methods**
  - **Merit**: real-time health monitoring
  - **Limitation**: only detection
    phenomenological model
- **Feature-based pattern recognition methods**
  - **Merit**: identification of damage location/severity
  - **Limitation**: large training data required for all different damage cases



Min et al. 2012

Impedance model-based methods

Background: Impedance-based Methods

Impedance data-based methods

Impedance model-based methods

- These methods are based on ***physical model* → *inverse problem:*** *identify system parameters (damage) of model based on measurements*
- **Merit:** Damage location/severity identification for new damage condition

  Sensor self-diagnosis,

  Optimize sensor deployment strategy
- **Various approaches**
  - FEM-based model updating (Tseng, et.al. 2005)
  - Spectral Element Method (SEM)-based model updating (Ritdumrongkul, et. al. 2005)
  - Sensitivity-based inverse problem using SEM (Wang, Tang. 2010)
- **Limitation:** *Seriously underdetermined* inverse problem

  Little consideration on the *noise and uncertainty in modeling*

Background: Underdetermined inverse problem

model, damage index, measurement

$$\mathbf{G} \times \delta\mathbf{d} = \delta\mathbf{Y}$$

→ *Moore-Penrose pseudoinverse*

$$\delta\tilde{\mathbf{d}} = \mathbf{G}^{-1}\delta\mathbf{Y}$$

$$= (\mathbf{V}\mathbf{S}^{-1}\mathbf{U}^{T})\delta\mathbf{Y}$$

$$\approx \sum_{i=1}^{n} \frac{\mathbf{u}_i^{T}\delta\mathbf{Y}}{s_i}\mathbf{v}_i$$

truncate the singular values

Error

$$\mathbf{G} \times \delta\mathbf{d} = \delta\mathbf{Y} + \mathbf{e}$$

$$\delta\mathbf{d}^{*} = \mathbf{G}^{-1}(\delta\mathbf{Y} + \mathbf{e})$$

$$= \delta\tilde{\mathbf{d}} + \mathbf{G}^{-1}\mathbf{e}$$

$$\approx \delta\tilde{\mathbf{d}} + \sum_{i=1}^{n} \frac{\mathbf{u}_i^{T}\mathbf{e}}{s_i}\mathbf{v}_i$$

very small singular values amplify the error term!

Damage identification is extremely sensitive to small errors for underdetermined inverse problem.

Problem Statement and Research Goal

Problem Statement

- The inverse problem for damage identification is significantly underdetermined ➔ Extremely sensitive to small errors such as environmental noise
- Accurate measurement of damage induced piezoelectric impedance variations, especially with noise

Research Goal

To overcome the limitations and develop a new method that can accurately and completely capture the damage features from piezoelectric impedance variations while still maintain the simplicity of the approach

Problem Statement and New Idea I

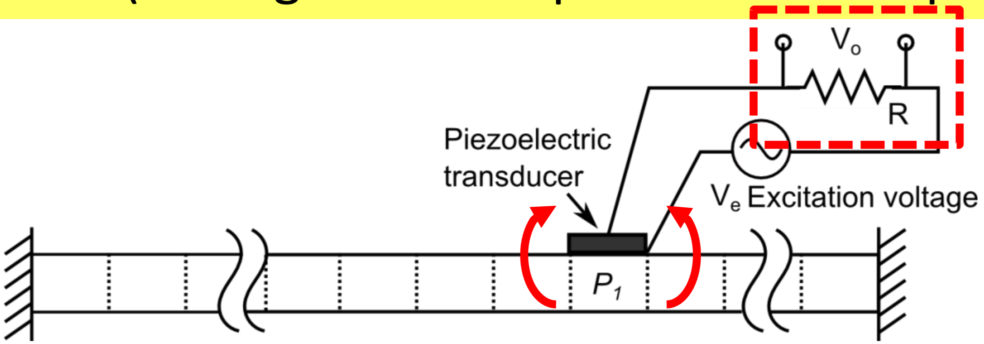
Problem Statement

- The inverse problem for damage identification is significantly underdetermined ➔ Extremely sensitive to small errors such as environmental noise
- Accurate measurement of damage induced piezoelectric impedance variations, especially with noise

New Idea: Impedance Data Enrichment via Adaptive Piezoelectric Circuitry

Sensitivity-based Inverse Problem Formulation

Derive $\boldsymbol{\delta}\mathbf{d}$ (location and severity of damage, e.g., stiffness reduction) based on $\boldsymbol{\delta}\mathbf{Y}$(damage-induced piezoelectric impedance variation) measurements



Generalized force by piezoelectric transducer

$$\mathbf{F} = M_p \boldsymbol{\Phi}_p^{\mathrm{T}}$$

Generalized displacement of the structure

$$\mathbf{W} = \mathbf{S}^{-1}(\omega)\mathbf{F}$$

Voltage generated by displacement

$$V_p = K_2 \boldsymbol{\Phi}_p \mathbf{W}$$

Impedance measured by the voltage across R

$$\Rightarrow \mathbf{Y} = \frac{1}{R}\frac{V_o}{V_e} = \frac{1}{R} K_2 \left[K_1 \boldsymbol{\Phi}_p \mathbf{S}^{-1}(\omega) \boldsymbol{\Phi}_p^{\mathrm{T}} + 1\right]$$

Cannot be accurately predicted!

First-order sensitivity equation

$$\mathbf{G} \times \boldsymbol{\delta}\mathbf{d} = \boldsymbol{\delta}\mathbf{Y}$$

$\mathbf{G}$: *m* x *N* sensitivity matrix

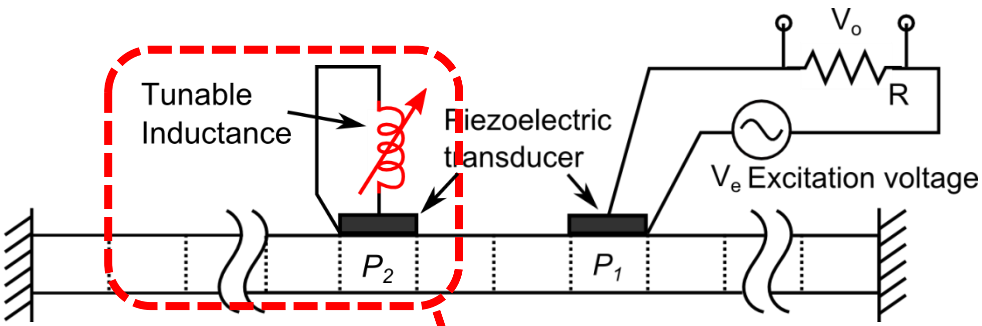
$\boldsymbol{\delta}\mathbf{Y}$: *m* x 1 vector of impedance variation ***measurements***

$\boldsymbol{\delta}\mathbf{d}$: *N* x 1 vector of ***damage index***

m* << *N

➔ *Underdetermined!*

New Idea: Impedance Data Enrichment via Adaptive Piezoelectric Circuitry

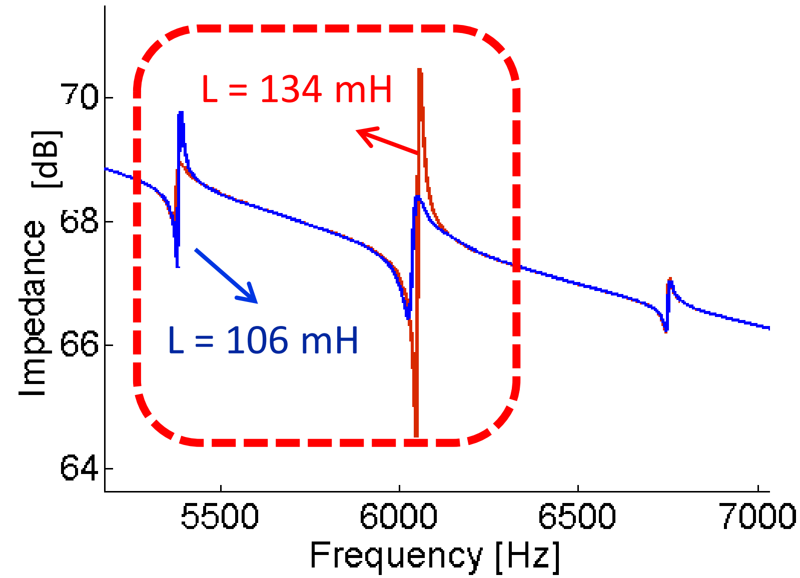


Generalized force by the additional piezoelectric transducer

$$\mathbf{F} = M_p \boldsymbol{\Phi}_p^{\mathrm{T}}$$

New dynamic stiffness matrix is adjustable via tuning inductance

$$\mathbf{W} = (\mathbf{S} \quad)^{-1} M_p \boldsymbol{\Phi}_p^{\mathrm{T}}$$

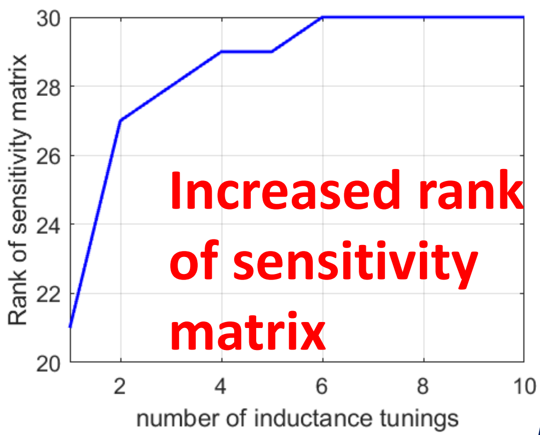


Tuning the inductance systematically can result in a ***family*** of impedance data

Greatly enrich the impedance measurement data and gain more information about the structural damage

New Idea: Impedance Data Enrichment via Adaptive Piezoelectric Circuitry

Tune the inductance to form a sequence, $L = [L_1, L_2, \dots L_n]$



$$\begin{bmatrix} \mathbf{G}(L_1) \\ \mathbf{G}(L_2) \\ \vdots \\ \mathbf{G}(L_n) \end{bmatrix} \times \delta\mathbf{d} = \begin{Bmatrix} \delta\mathbf{Y}(L_1) \\ \delta\mathbf{Y}(L_2) \\ \vdots \\ \delta\mathbf{Y}(L_n) \end{Bmatrix}$$

Significantly increased # of impedance measurements

Much more information!

Merit of the proposed idea: Original underdetermined inverse problem can be greatly improved!

Numerical Analysis: Damage Identification

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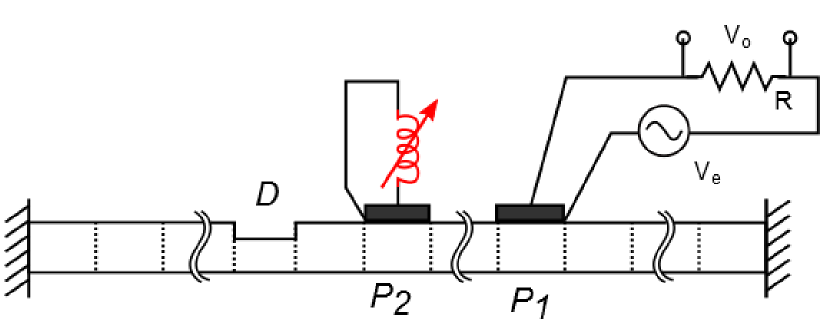
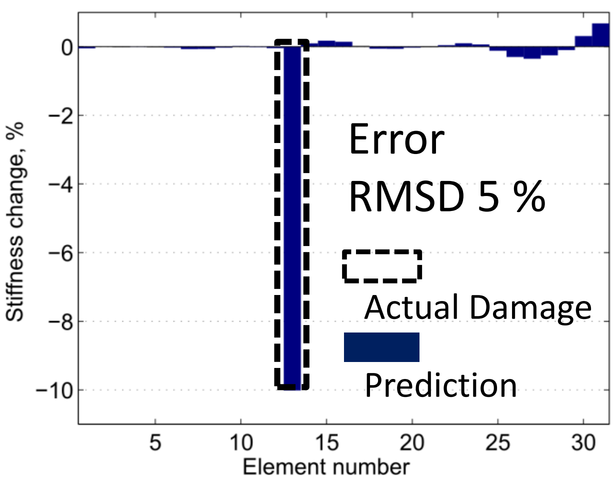


- **Damage**: 10% stiffness loss at the 13th element of total 31 elements
- **Data enrichment**: Adaptive piezoelectric circuit with 8 different inductances at the 3rd element

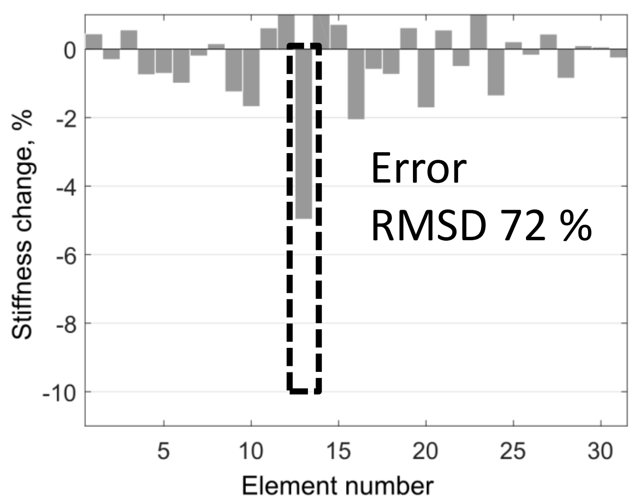
$$RMSD = \sqrt{\frac{\sum(\delta \boldsymbol{d}_{predict} - \delta \boldsymbol{d}_{actual})^2}{\sum(\delta \boldsymbol{d}_{actual})^2}}$$

No.	1	2	3	4	5	6	7	8
L [mH]	134.6	106.4	85.1	68.9	56.4	46.6	38.8	32.6

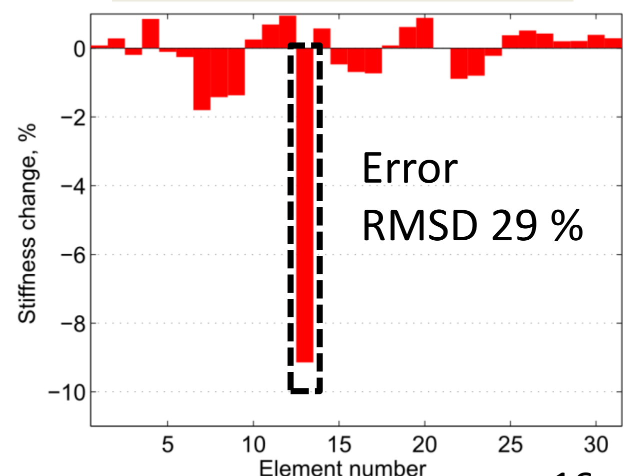
Conventional method wo/ noise



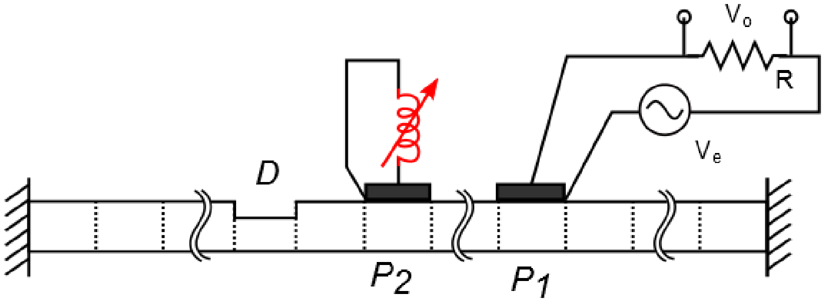
Conventional method w/ noise, 62dB SNR



Data enrichment w/ noise, 62dB SNR



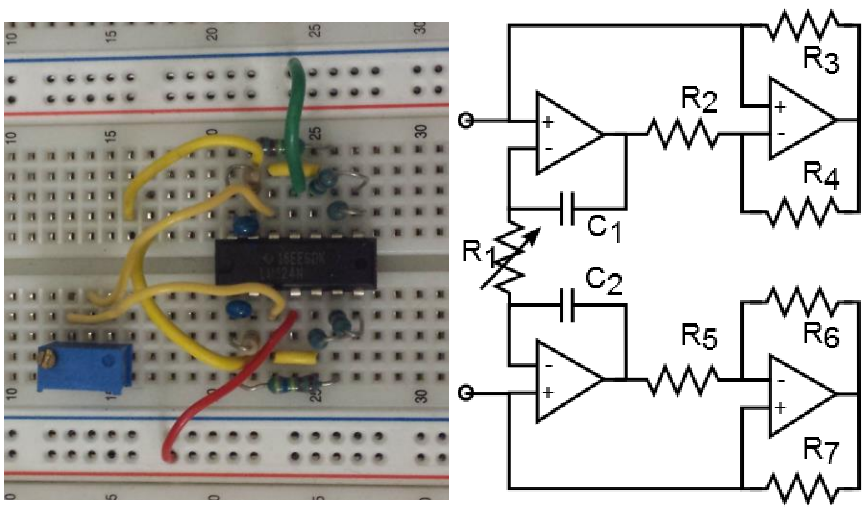
Experimental Verification



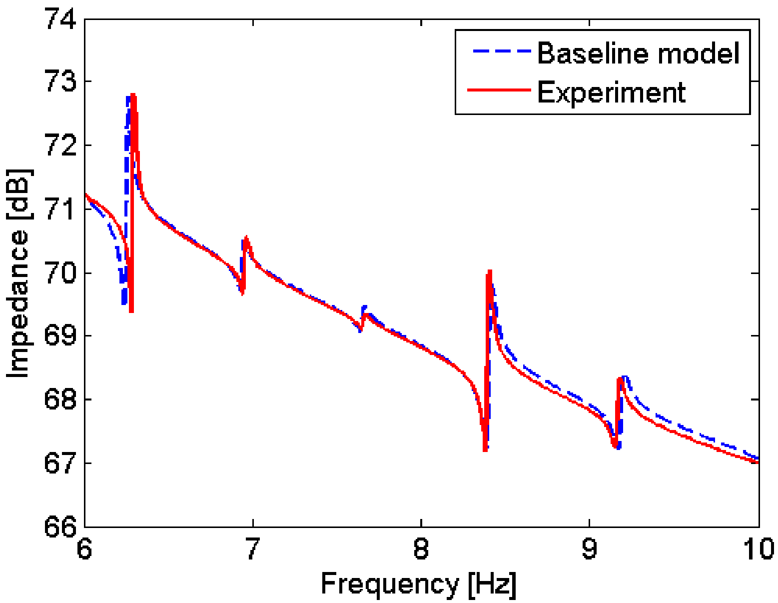
	Elem.	Dimension
Beam structure (Al-2024)	61	627 x 7.21 x 3.175 mm
PZT (PSI-5A4E)	41 / 29	16.8 x 7.09 x 0.191 mm
Damage	25	Notch: 10.4 mm x 90 um → 8.3 % loss

7 Inductance tunings in 6 kHz – 10 kHz

No.	1	2	3	4	5	6	7
L, mH	39.5	40.4	41.3	45.3	46.2	63.1	80.1

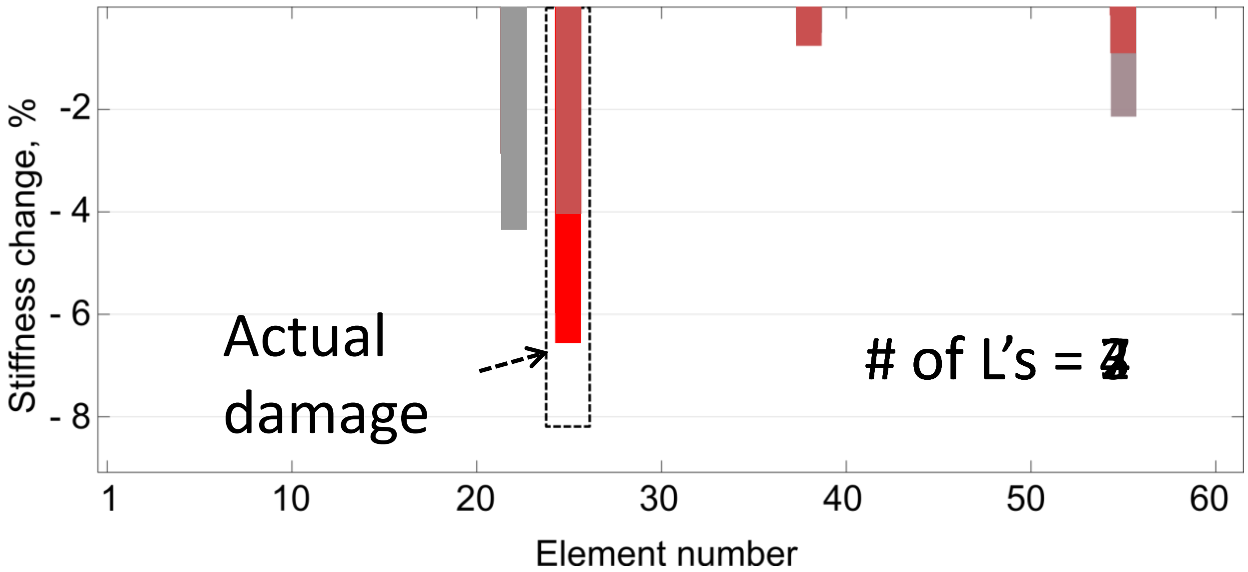


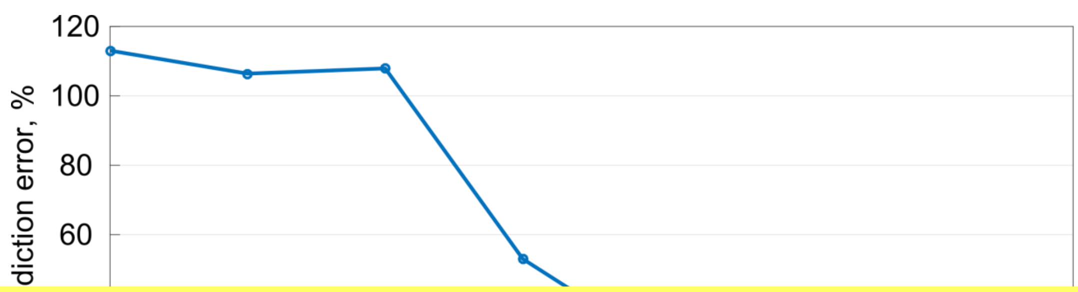
synthetic tunable inductor



Experimental Verification

- Damage Identification Results





The concept of data enrichment for improving damage identification is experimentally verified.

Problem Statement and New Idea II

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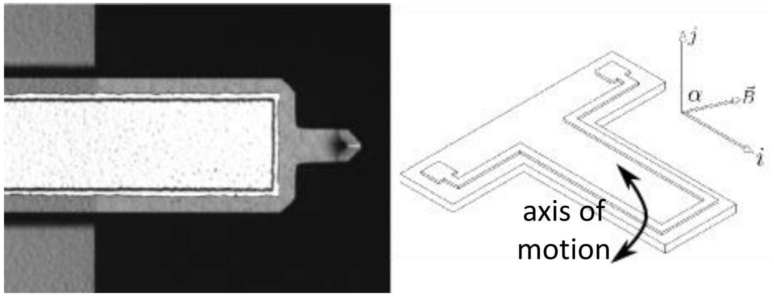
Problem Statement

- The sensitivity-based inverse problem is significantly underdetermined → Extremely sensitive to small errors such as environmental noise, uncertainty in modeling
- Accurate measurement of damage induced piezoelectric impedance variations, especially with noise

New Idea: Damage Identification Enhancement with Integrated Bistable and Adaptive piezoelectric Circuitry

Bifurcation-Based Sensing in MEMS

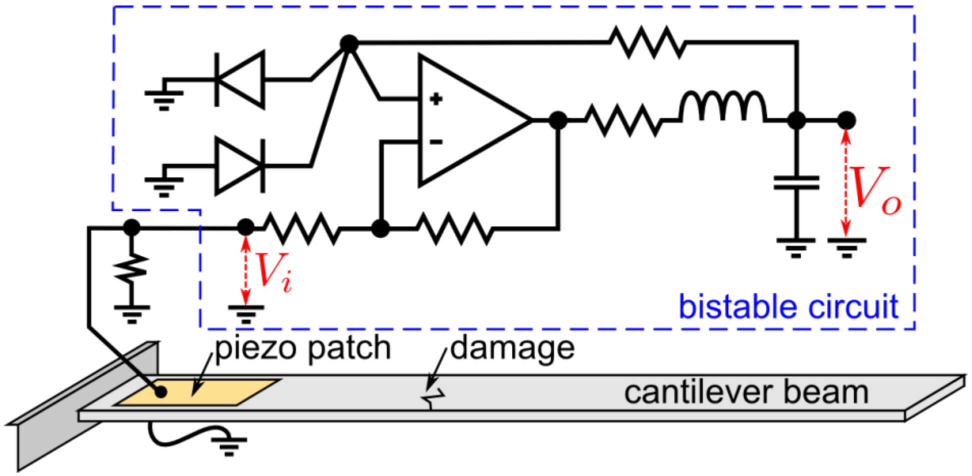
- **Bifurcation**: large qualitative response change (e.g., transition from low- to high-amplitude response, or high-low) due to crossing critical parameters of a nonlinear system
- Microscale (MEMS) mass detection using bifurcations recently studied (Zhang and Turner, 2005; Kumar, et al., 2011)
- Determination of mass accumulation shown to be less susceptible to *noise and damping* than direct frequency peak measurements.



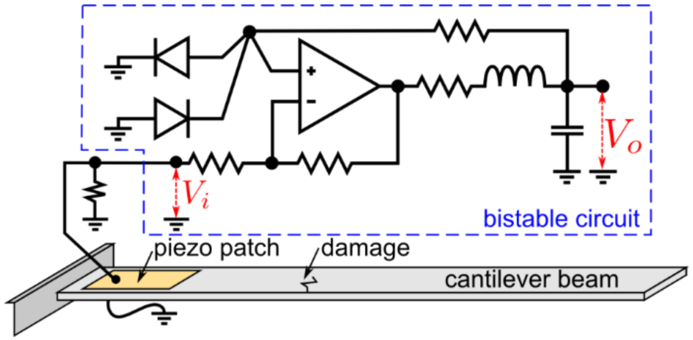
Bifurcation-based mass sensor: piezoelectrically actuated micro-cantilever, Kumar et al 2011

New Idea: Bistable Circuitry for Bifurcation-Based Sensing for Macro-Structures

- Most structural systems to monitor for damage are not strongly nonlinear ➔ Need additional means to introduce strong nonlinearity for bifurcation-based detection
- New Idea: ***Bistable circuitry*** integrated with host structure through piezoelectric transducer
  - The structural response (V_i from the piezo-transducer) is *input* for the bistable circuit, and can activate the circuit output voltage V_o bifurcations
  - Negligible back-coupling inhibits interaction between circuit responses and structural dynamics

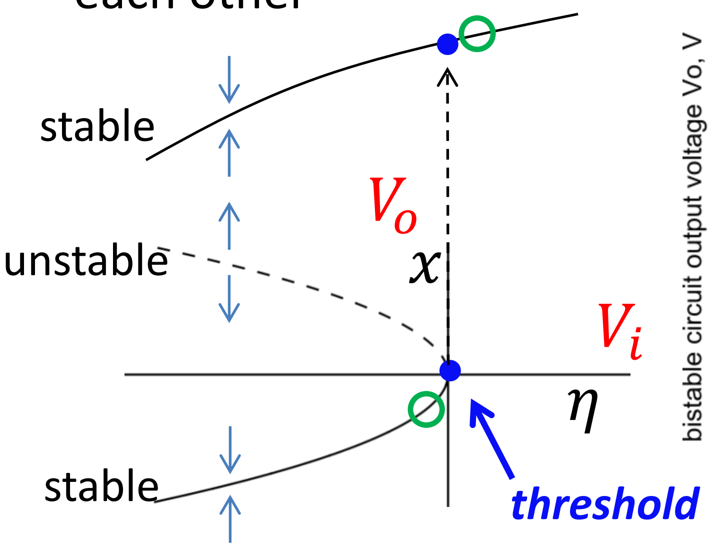


Bistable Circuitry: Experimental Investigation



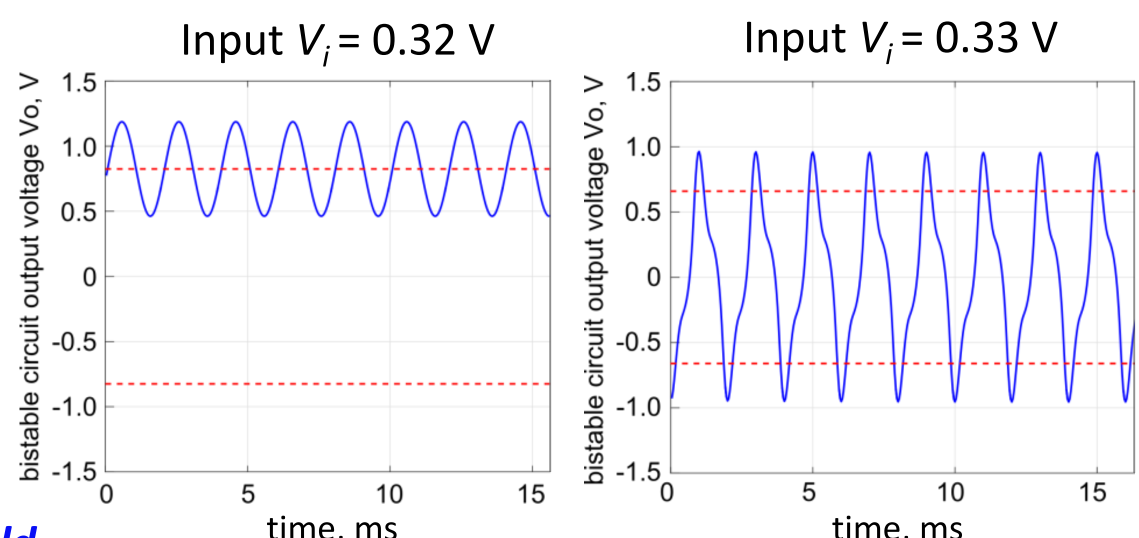
Saddle-node bifurcation

➔ two equilibria of a dynamical system *collide* each other

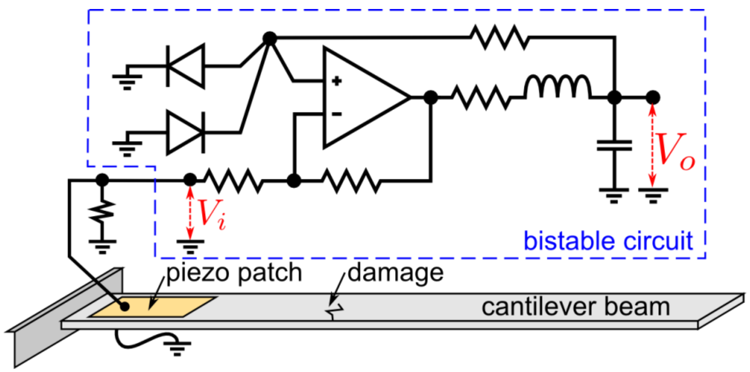


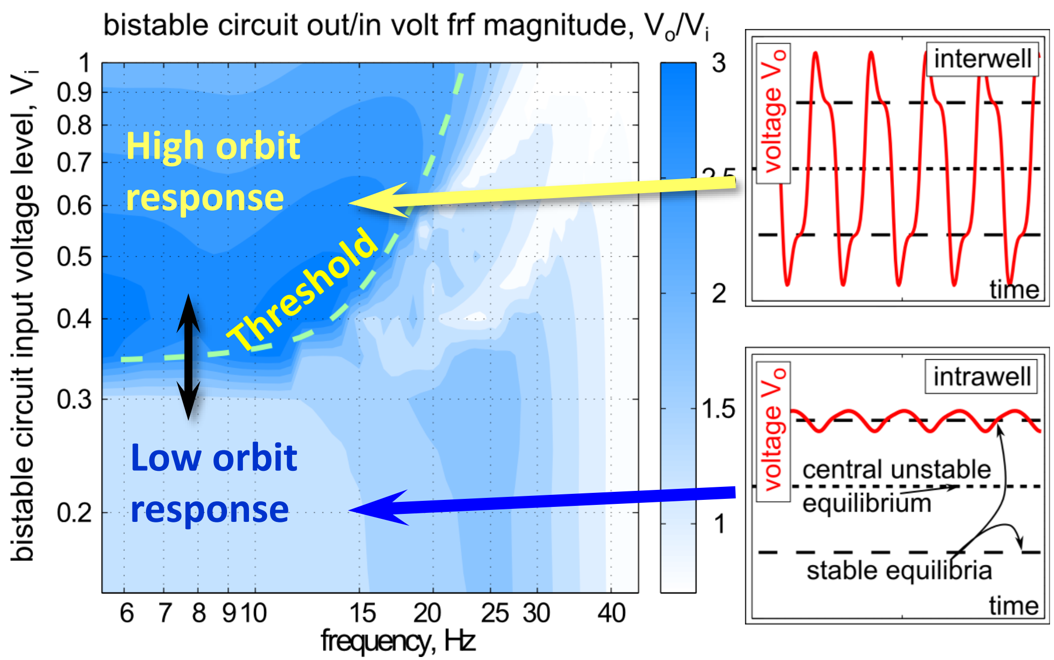
- **Saddle-node bifurcation with respect to input amplitude**
  - Sudden transition from low orbit to high orbit oscillation *when the input amplitude passes a* ***threshold*** → ***onset*** of saddle-node bifurcation

Bistable circuit response in time



Bistable Circuitry: Experimental Investigation

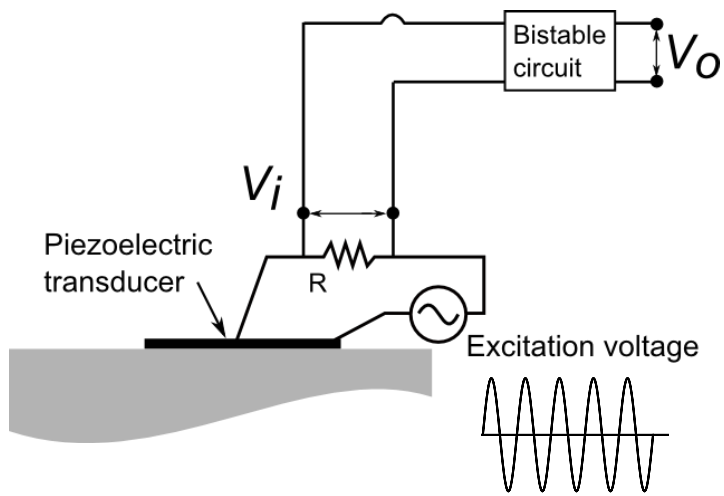


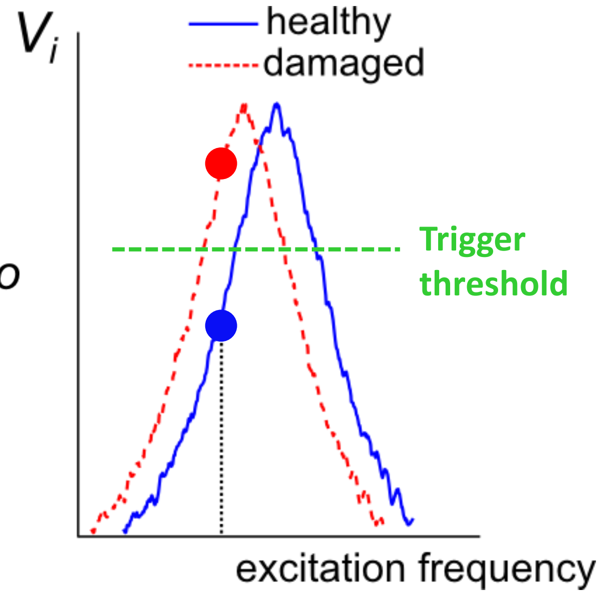


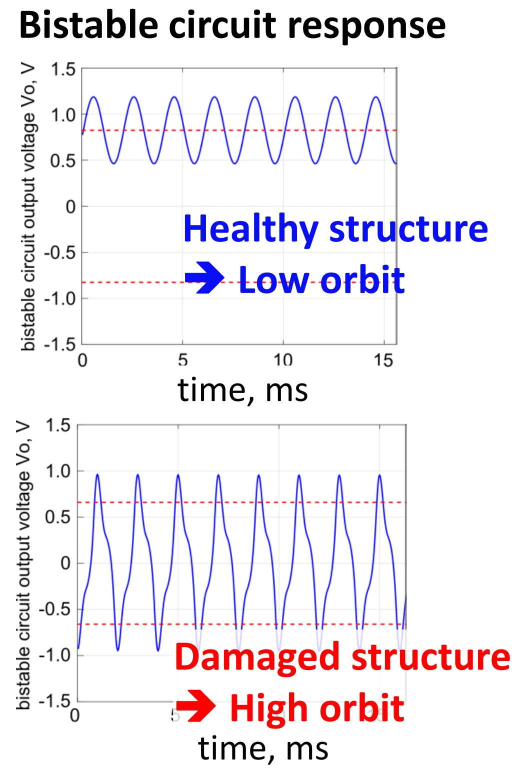
- Bistable circuit response dependent upon excitation frequency and level
- Measured circuit FRF amplitude showing critical region of bifurcation activation with clear **threshold**

To detect damage-induced impedance variations -- Tune bistable sensitivity to target a specific structural mode

Measuring impedance variations from Bifurcation Activation

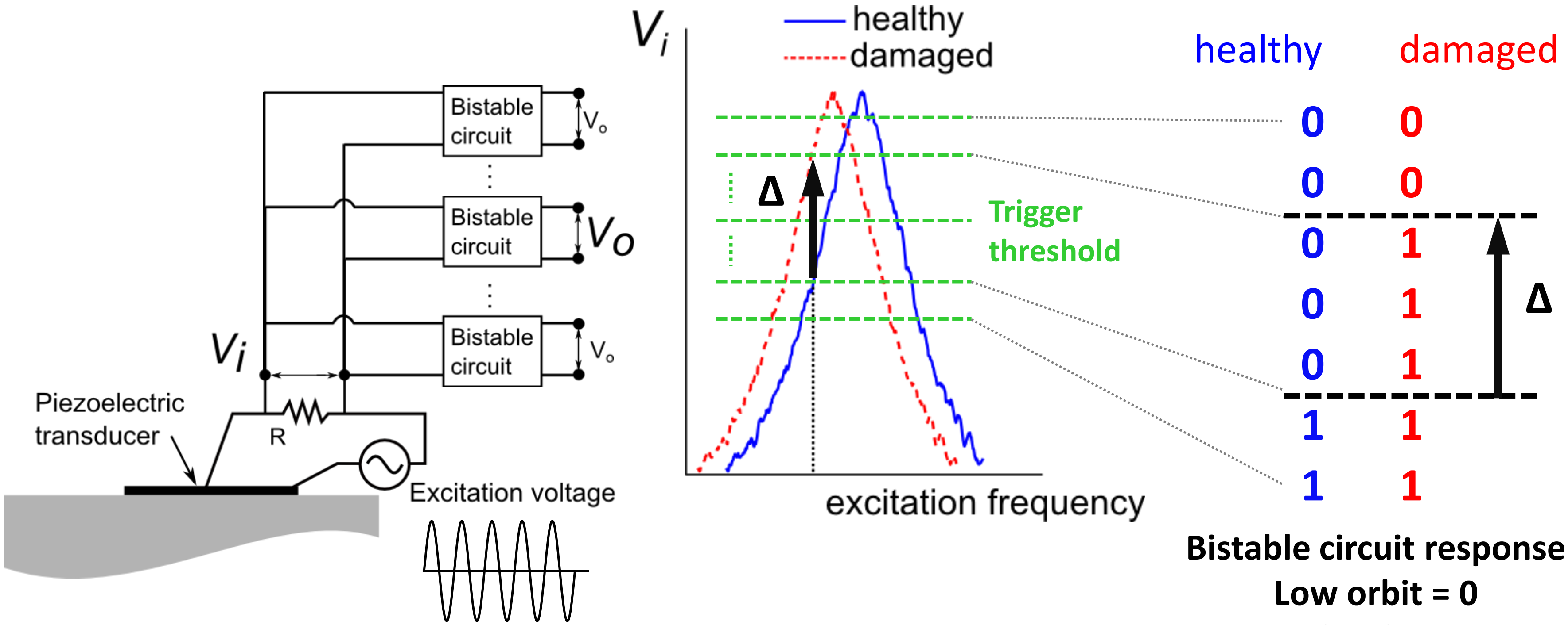






- Use host structural response before/after damage as input voltage for a bistable circuit
- A critical level of host structural response will trigger bifurcation

Measuring impedance variations from Bifurcation Activation



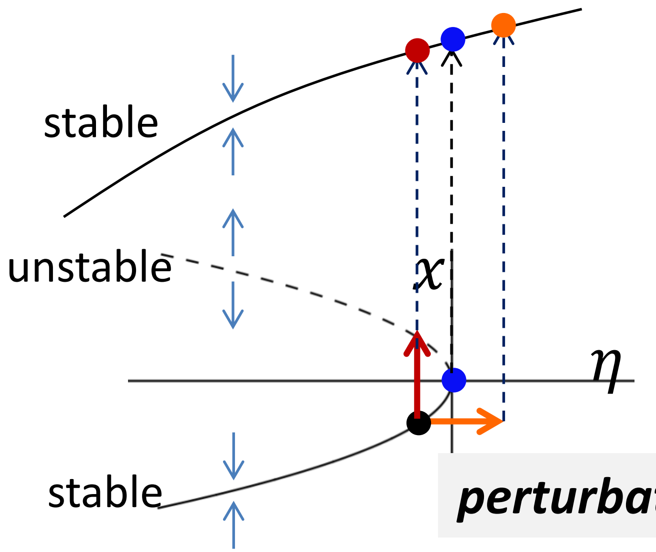
Bistable circuit response
Low orbit = 0
High orbit = 1

- Use host structural response before/after damage as input voltage for ***an array of bistable circuit with various threshold levels***
- A critical level of host structural response will trigger bifurcation

Provide robust measurements of impedance variation for damage ID

Non-stationary and stochastic influences on saddle-node bifurcation

- Damage-induced impedance variation measurement ***by tracking the onset of bifurcation***



perturbation

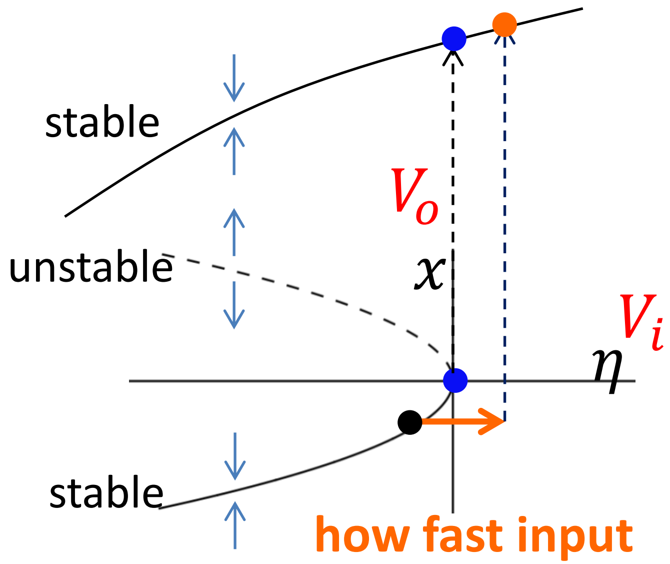
Saddle-node bifurcation

Sudden transition/escape to another stable state *when the input amplitude passes a* ***threshold*** → ***onset*** of saddle-node bifurcation

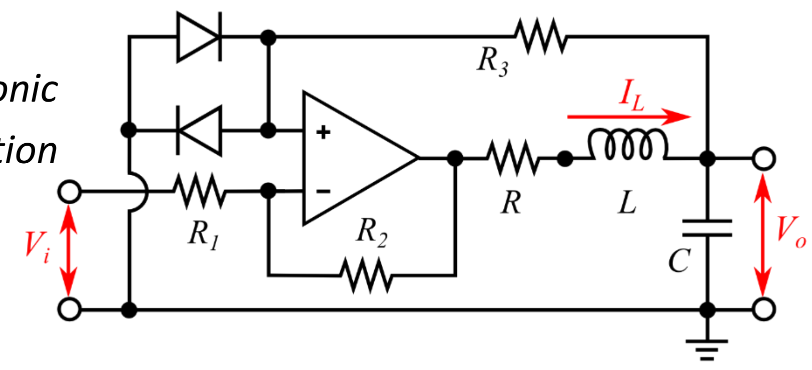
Noise, non-stationary effects influence the onset of bifurcation

Accurate assessment on the onset of saddle-node bifurcation is critical for sensing application

Non-stationary and stochastic influences on saddle-node bifurcation

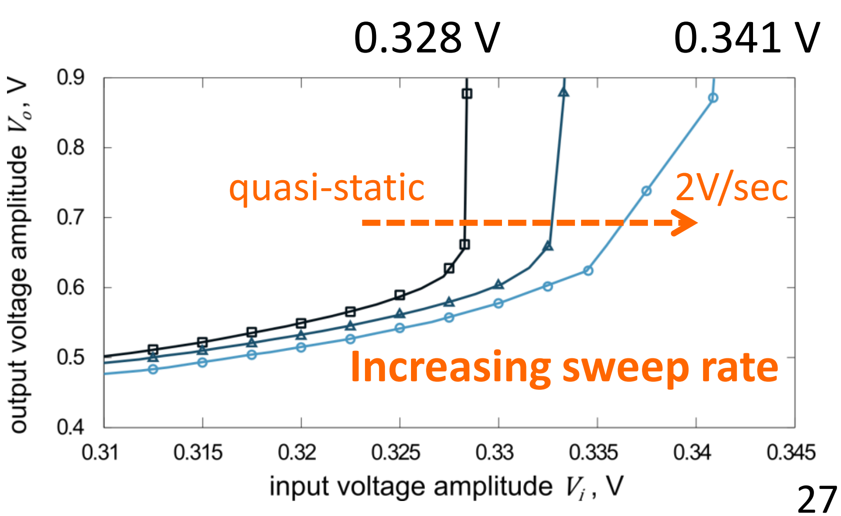


how fast input amplitude increases

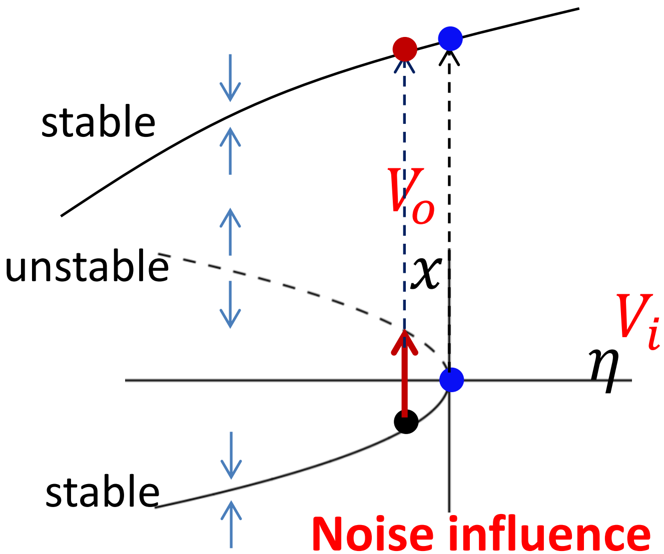


L, mH	C, nF	R, Ω	R_1, kΩ	R_2, kΩ	R_3, kΩ
20	47	32	1	1	2

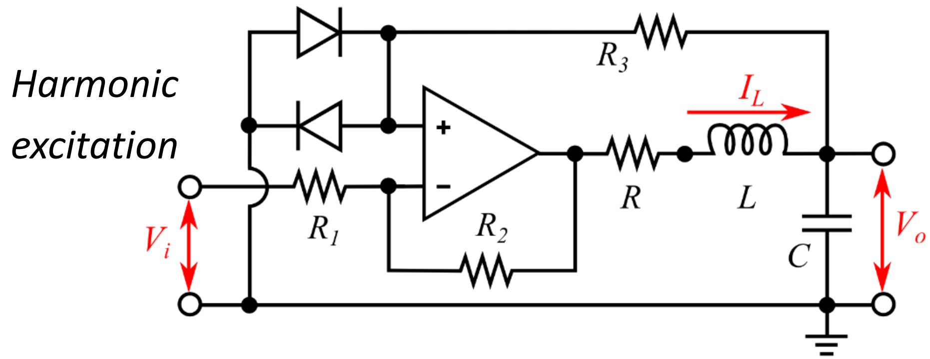
- **Non-stationary influence**
  - Change input amplitude sweep rate (quasi-static – 2 V/sec)
  - The onset of <u>bifurcation is delayed</u>



Non-stationary and stochastic influences on saddle-node bifurcation

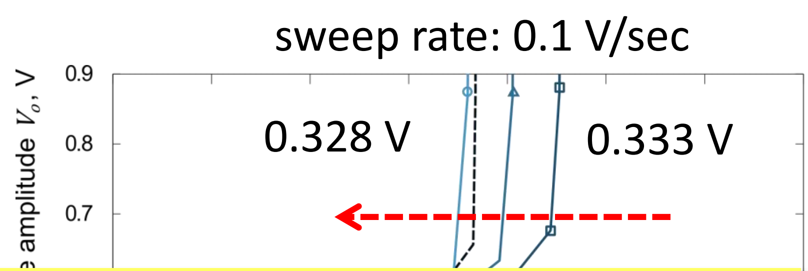


Noise influence on input voltage



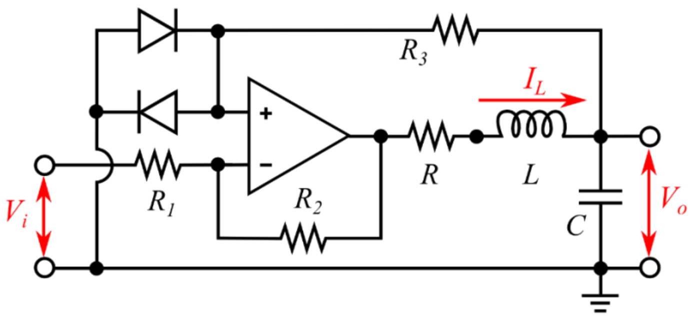
L, mH	C, nF	R, Ω	R_1, kΩ	R_2, kΩ	R_3, kΩ
20	47	32	1	1	2

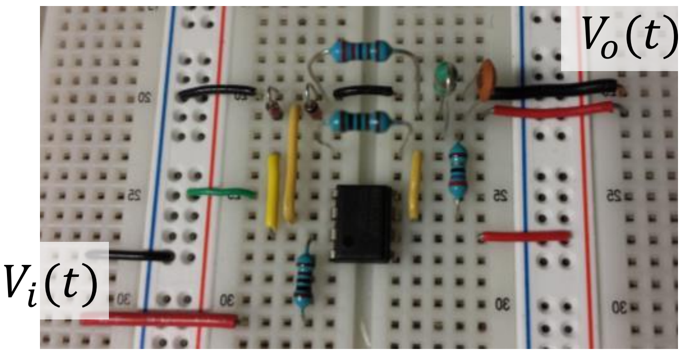
- **Stochastic influence**
  - Additive Gaussian white noise (1 mV – 20 mV)



Saddle-node bifurcation is extremely sensitive to stochastic and non-stationary influences

Theoretical model of the bistable circuit



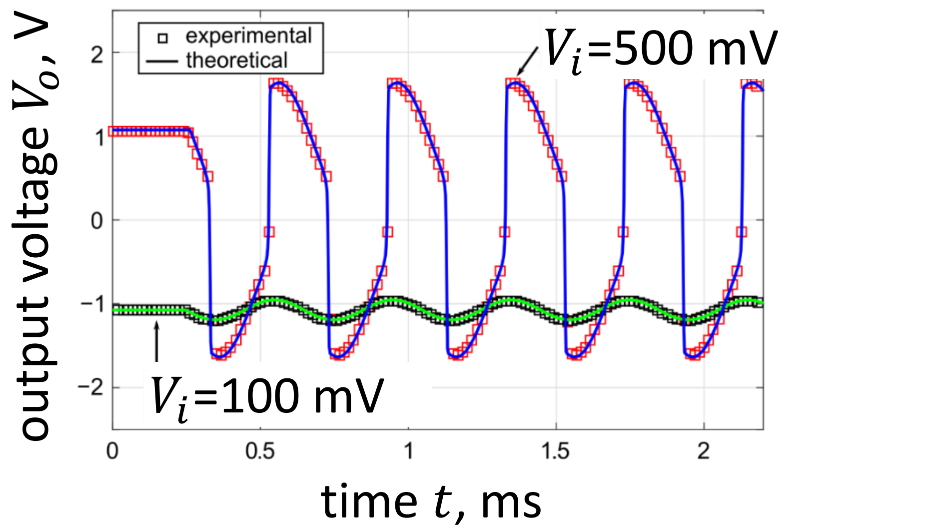


$$L\frac{dI_L}{dt} = (g-1)V_D - I_L R - 2R_3 I_s \sinh\left(\frac{V_D}{\eta V_T}\right) + (1-g)V_i$$

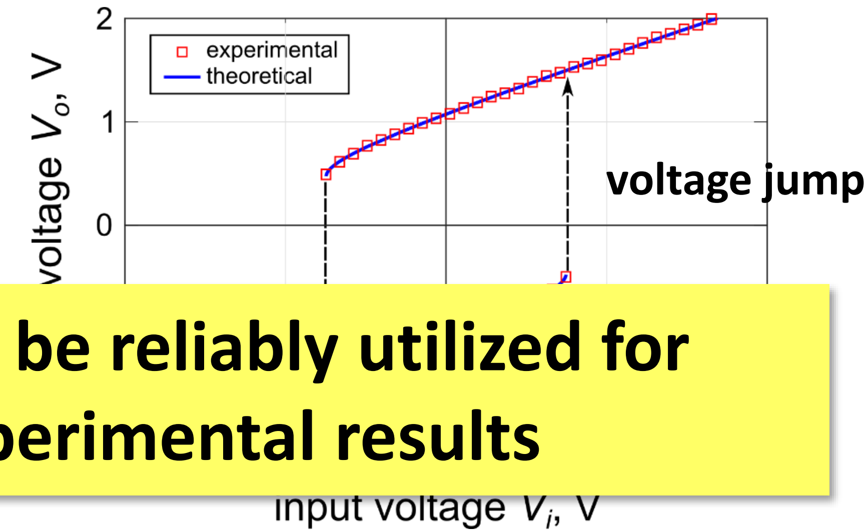
C [illegible]

$$V_o = V_D + 2R_3 I_s \sinh\left(\frac{\ldots}{\eta V_T}\right)$$

AC input voltage at 2.5 kHz

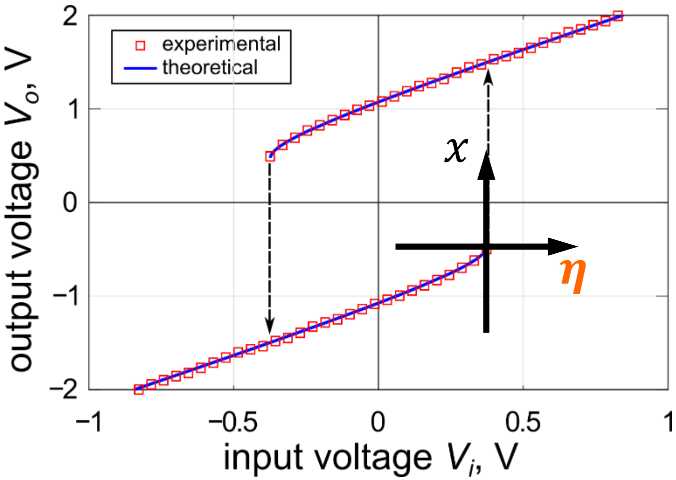


DC input voltage sweep



Numerical analysis can be reliably utilized for estimating the experimental results

Single-parameter stochastic normal form with non-stationary influence



Approximate the local dynamics near bifurcation point as piecewise-linear system

$$RC\dot{V}_o + aV_o + b = V_i + nW$$

Stochastic normal form of non-smooth saddle-node bifurcation

Gaussian white noise

$$\dot{x} = \eta + |x| + \varepsilon\,\xi \qquad \langle \xi(t), \xi(\tilde{t}) \rangle = 2\delta(t - \tilde{t})$$

bifurcation parameter   noise strength

Non-stationary influence: $\eta(t) = \eta_0 + r\,t, \qquad \eta_0 < 0$

parameter sweep rate

Change of variables $\tau = \eta\, r^{-1}$

new time scale

$z = x\, r^{-1}$

Sing

Investigate the stochastic and non-stationary influences using single parameter, scaled noise α

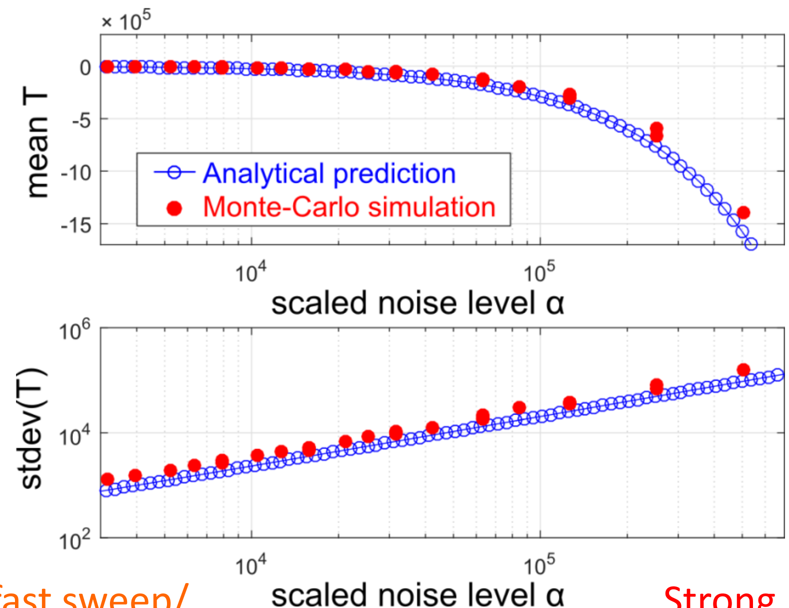
Numerical verification of analytical escape probability distribution

- Analytical prediction of escape time *T, where* $z(T) \rightarrow \infty$
  - Fokker-Planck equation
  - Kramer's escape rate

$$\frac{\partial P(z,t)}{\partial t} = -\frac{\partial}{\partial z}[(t+z^2)P] + \alpha^2 \frac{\partial^2 P}{\partial x^2}$$

$$P(T) = W(T)\exp\left(-\int_{t_0}^{T} W(t)dt\right) \quad W(t) = \frac{\sqrt{-t}}{\pi}\exp\left(-\frac{4(-t)^{3/2}}{3\alpha^2}\right)$$

- Numerical verification
  - Monte-Carlo method: solve stochastic differential equation of the bistable circuit via Euler-Maruyama approach

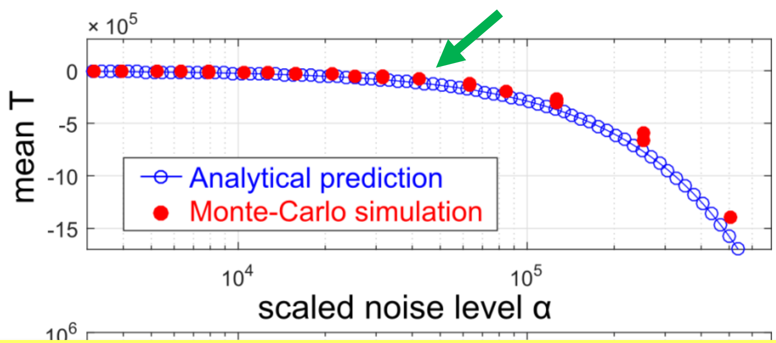


fast sweep/ weak noise ⟵ ⟶ Strong noise/ slow sweep

- Noise level
  ➔ 2.5, 5, 10, 20 40 mV rms
- Input amplitude sweep rate
  ➔ 10, 20, 40, 60, 80, 200 mV/sec

Numerical verification of analytical escape probability distribution

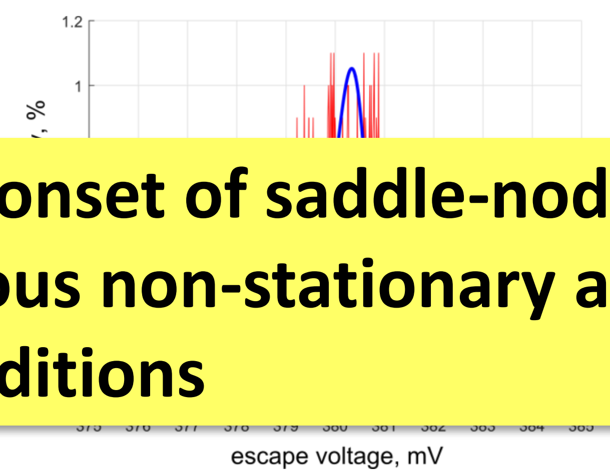
- Analytical prediction of escape time *T, where* $z(T) \to \infty$
  - Fokker-Planck equation $\frac{\partial P(z,t)}{\partial t} = -\frac{\partial}{\partial z}[(t+z^2)P] + \alpha^2 \frac{\partial^2 P}{\partial x^2}$
  - Kramer's escape rate $P(T) = W(T)\exp\left(-\int_{t_0}^{T} W(t)dt\right) \quad W(t) = \frac{\sqrt{-t}}{\pi}\exp\left(-\frac{4(-t)^{3/2}}{3\alpha^2}\right)$
- Numerical verification
  - Monte-Carlo method: solve stochastic differential equation of the bistable circuit via Euler-Maruyama approach



Noise level: 10 mV rms

Sweep rate: 40 mV/sec

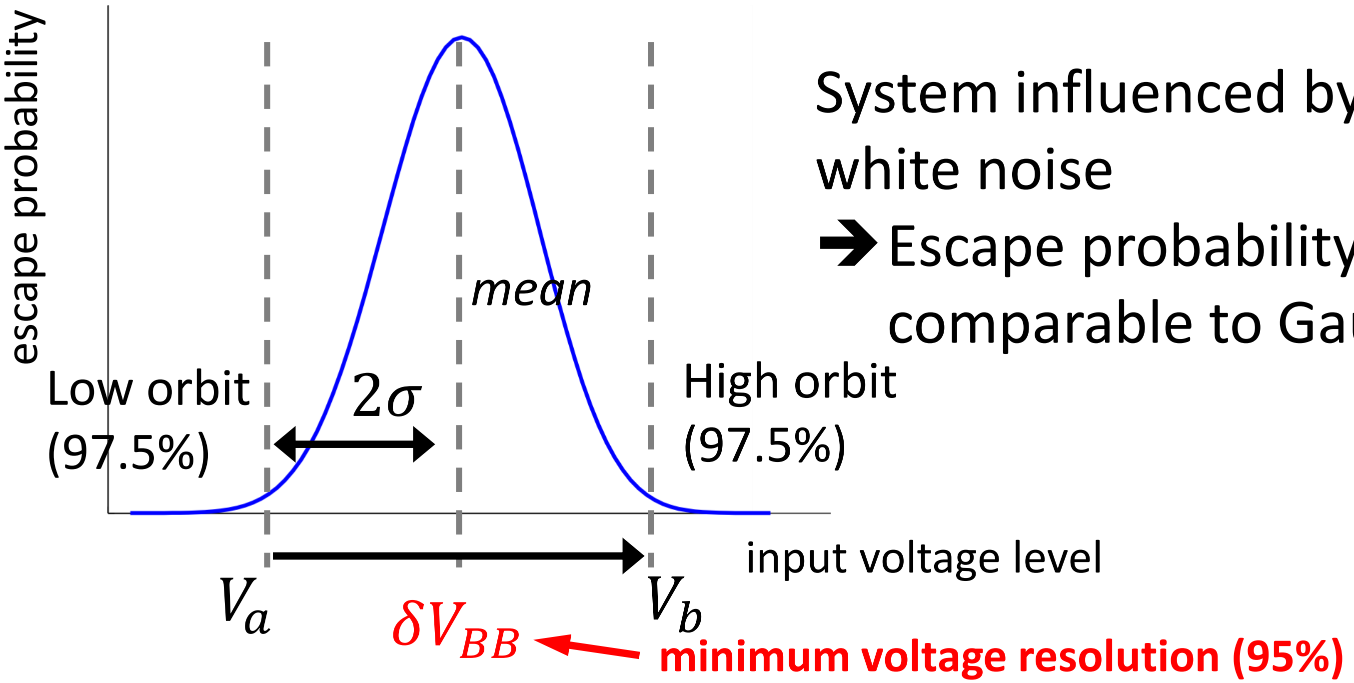
onset of saddle-node bifurcation



Analytical prediction on the onset of saddle-node bifurcation is verified for various non-stationary and stochastic conditions

weak noise ⟵ - - - - ⟶ slow sweep

Escape probability distribution and bifurcation-based sensing resolution



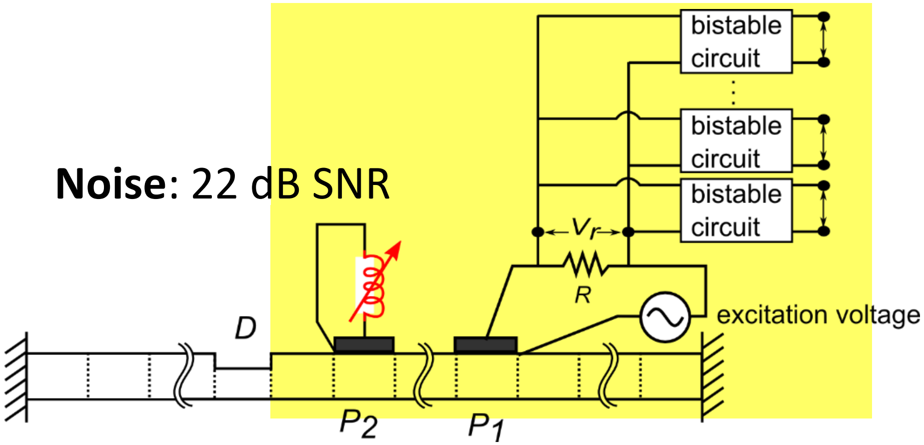
System influenced by Gaussian white noise
➔ Escape probability distribution comparable to Gaussian.

- Case: noise level (10 mV), sweep rate (40 mV/s)
- A

Theoretical framework enables to determine the enhanced minimum resolution of bifurcation-based sensing approach

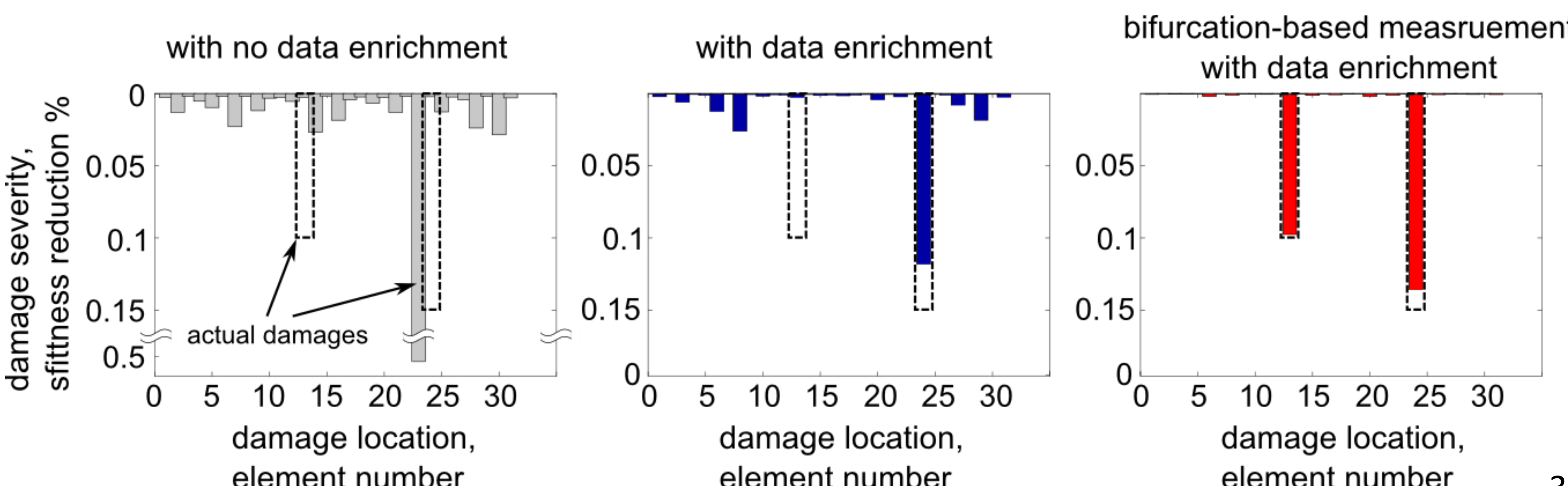
Damage Identification with Integrated Bistable and Adaptive Piezoelectric Circuitry

Noise: 22 dB SNR



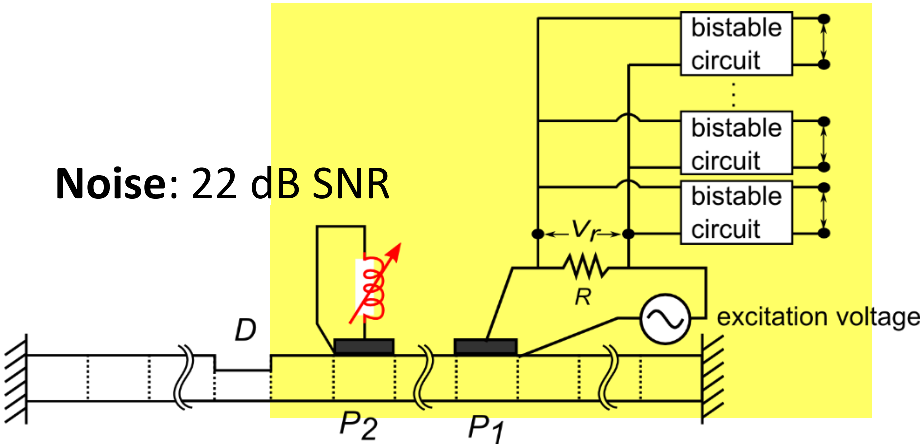
Damages: 0.1%, 0.15% element stiffness reduction @ 13th, 24th element

- **Data enrichment**
  - Adaptive piezoelectric circuit with 7 different inductances
- **Impedance measurement**
  - Bistable circuitry integrated with piezoelectric circuitry



Damage Identification with Integrated Bistable and Adaptive Piezoelectric Circuitry

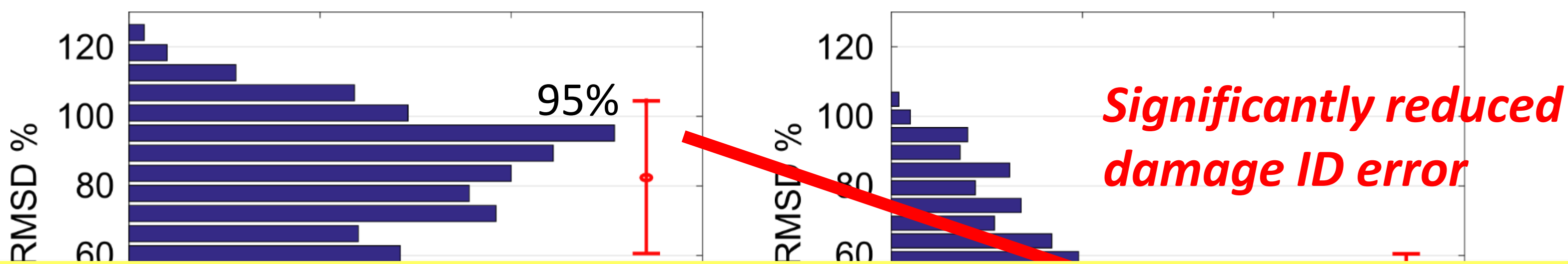
Noise: 22 dB SNR



- **Damage identification for various cases:** 1000 combinations of
  - 0.5, 1, 1.5, or 2% element stiffness reduction,
  - 1, 2, or 3 locations of damages.

Data enrichment with **conventional** measurement

Data enrichment with **bifurcation-based** measurement



Damage identification via integrated bistable and adaptive piezoelectric circuitry is much more accurate and robust

count

count

Summary and Conclusion

- **Develop integrated bistable and adaptive piezoelectric circuitry**

  ➔ Fundamental improvement of underdetermined inverse problem for damage identification

- **Create bistable circuitry sensing platform**

  ➔ Key element to extend the applicability of bifurcation-based sensing scheme

- **Establish novel analysis on stochastic and dynamic saddle-node bifurcation**

  ➔ Simple and accurate prediction of the critical conditions of various disciplines that exhibit saddle-node bifurcation

  ➔ Fundamental understanding of the sensing limit under noise and non-stationary influences.

Future Plans

Vison: Advance System Monitoring and Sensing Strategies for Sustainable and Resilient System Health Management

- **Structural health monitoring**
  - → Measurement and modeling uncertainty quantification/management
  - → Long-term goal: Prognosis and decision-making for maintenance
  - → Collaboration with UTC in engine health monitoring
- **Bifurcation-based bistable circuitry sensors**
  - → Various bistable circuitry architecture and optimal parameter design
  - → Application with MEMS sensors for HVAC systems → medical, safety
- **Forecasting critical transitions in complex systems**
  - → Nonlinear bifurcation prediction + model-less data-driven approach
  - → Ecological and climate systems to aero-elasticity in aircraft, power grid systems

The End

Questions?