System Tools Applied To Microcantilever Based Devices

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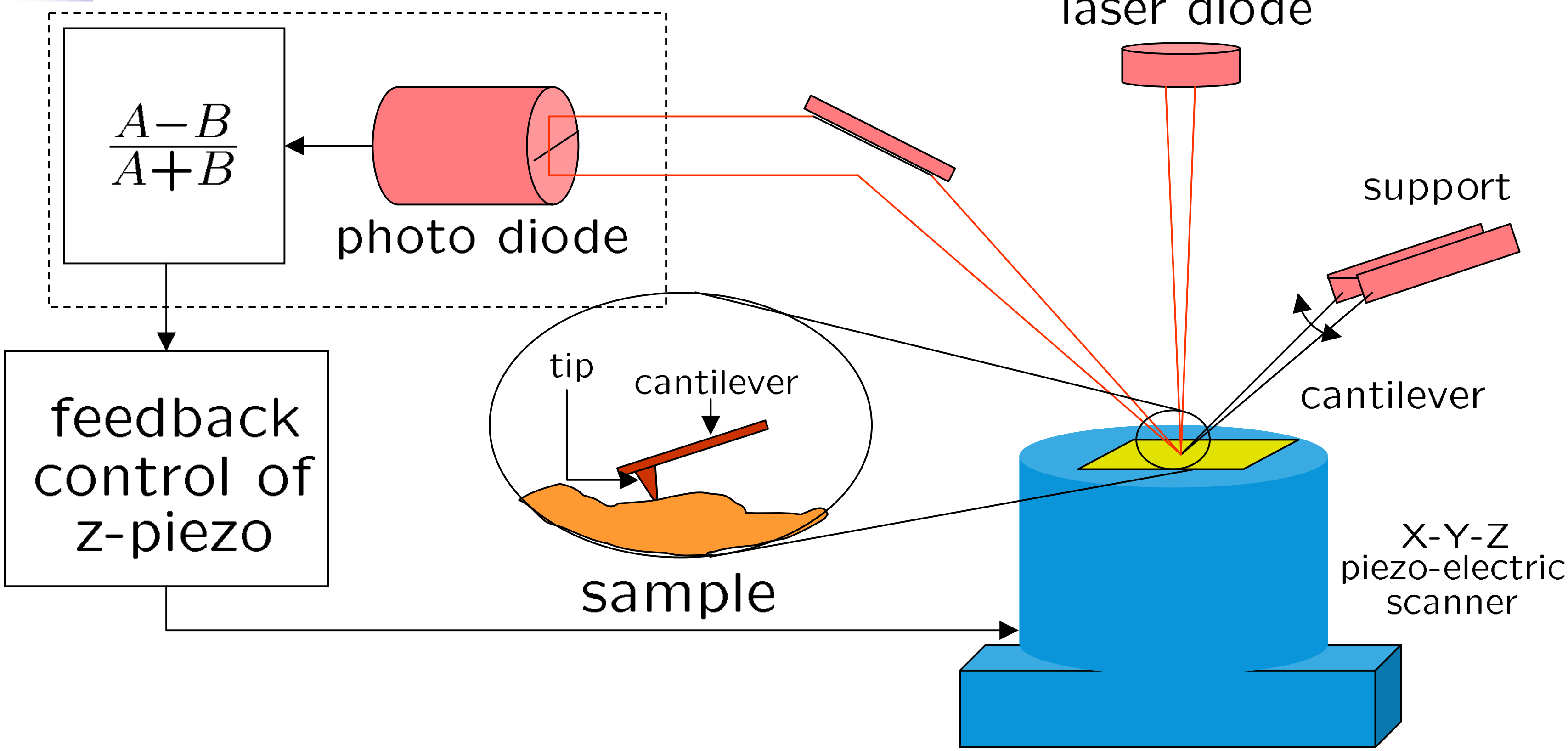
OUTLINE

- Introduction
- Interrogation
  - Thermal noise response
  - Complex dynamics
  - Systems Viewpoint
- Nanopositioning
  - Constraints and specifications
  - Multi-objective robust control design
- Conclusions and future directions

ATOMIC FORCE MICROSCOPES



Minimum detectable cantilever deflection = $0.01nm$ Spring constant of cantilever = $0.01-100N/m$ Tip-sample force control = $1-100pN$ Force needed to break a hydrogen bond = $1-10pN$	typical cantilever parameters: L = $100-200\mu m$ b = $5-10\mu m$ tip = $5nm$

AFM's Atomic Scale Resolution

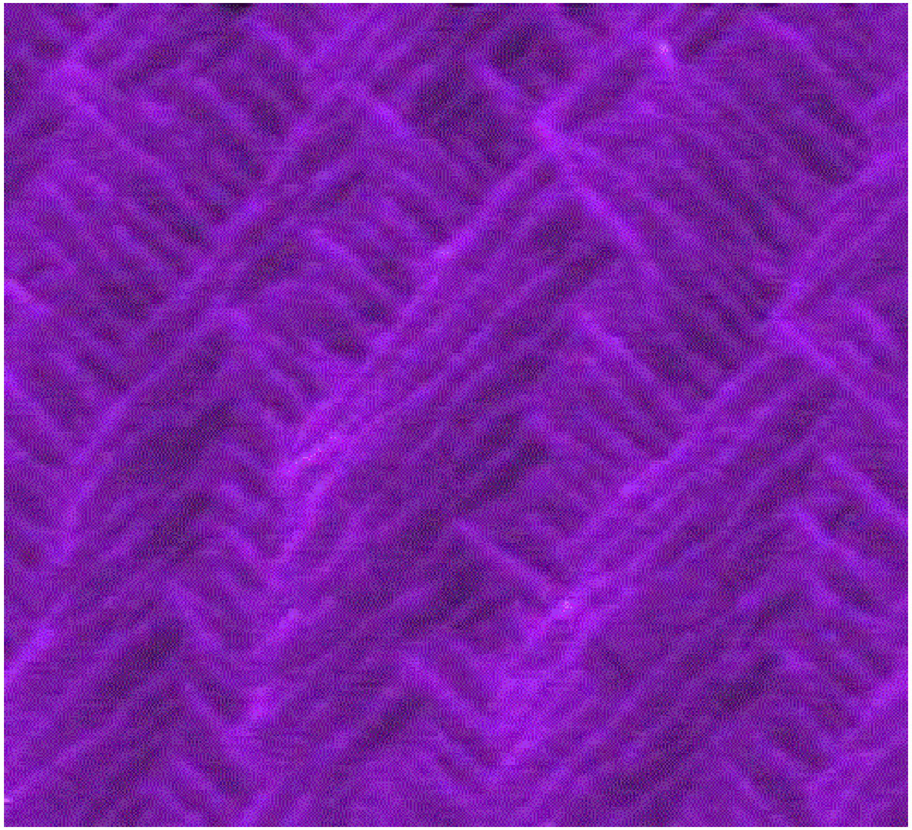


Image taken with *NanoScope SPM (Digital Instruments, Santa Barbara, CA)*

- Tapping mode image of single-atom terracing and fingering on an as-received 6" homo-epitaxial silicon wafer. The terraces, which step up from the upper left to the lower right of the image, are 0.14nm high

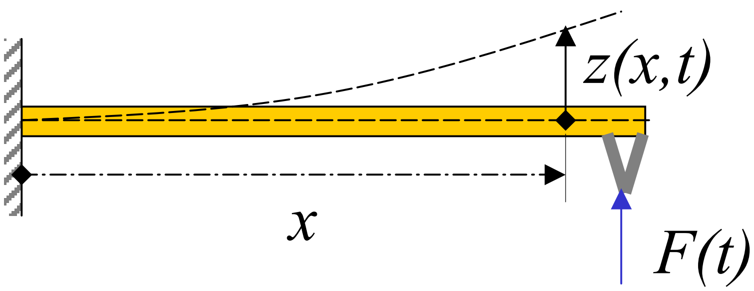
APPLICATIONS

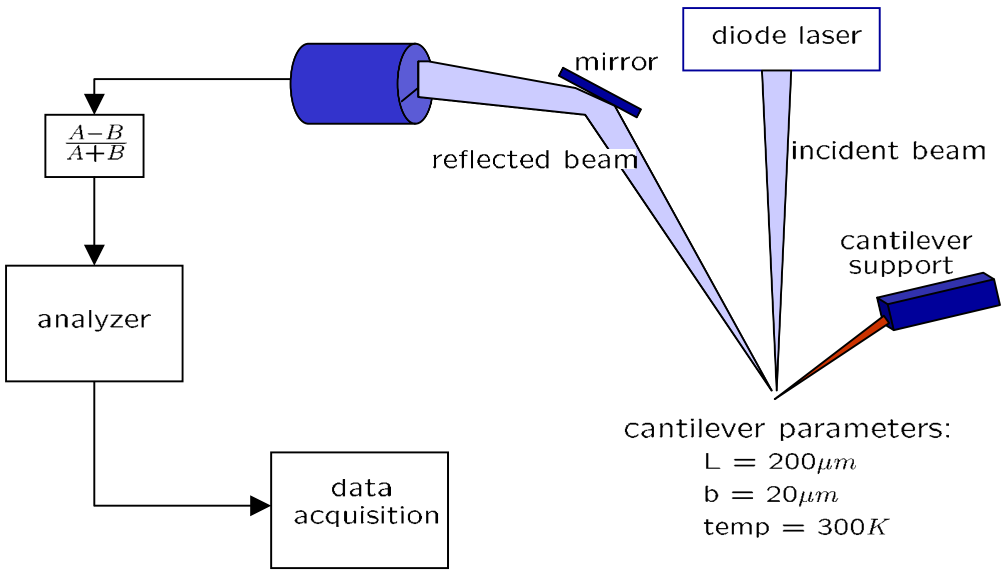
- Microcantilever employed to investigate electron spin dynamics
  - Applications to unraveling electronic structure of material
  - Quantum computers

- Applications to biology
  - Cell dynamics
  - Gene mapping

Sample Interrogation

THERMAL NOISE BASED IDENTIFICATION



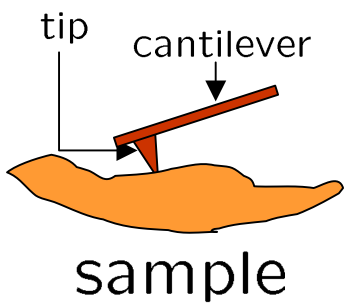


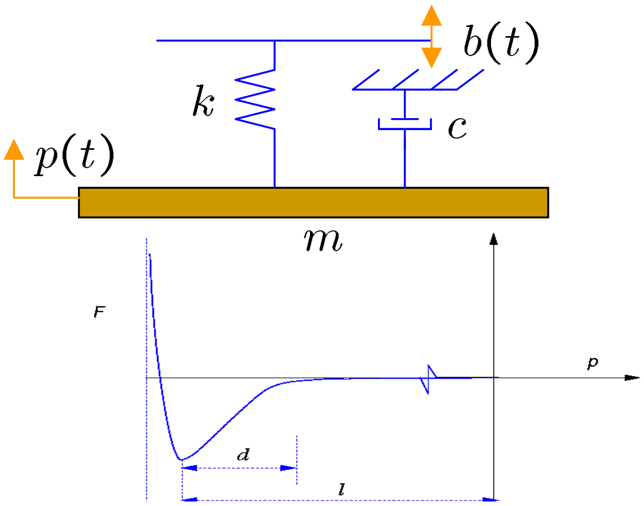
- $S_{zz}(\omega, x) = \sum_{j=1}^{N} \frac{2k_B T c_j}{(k_j - m_j\omega^2)^2 + c_j\omega^2}\phi_j^2(x)$

- The power spectral density plot can be used to estimate cantilever parameters precisely.

Joint work with, Bergh, Lai, Majumdar and McFarland
Multimode noise analysis of cantilevers for scanning probe microscop, Journal of Applied Physics,

Complex Dynamics

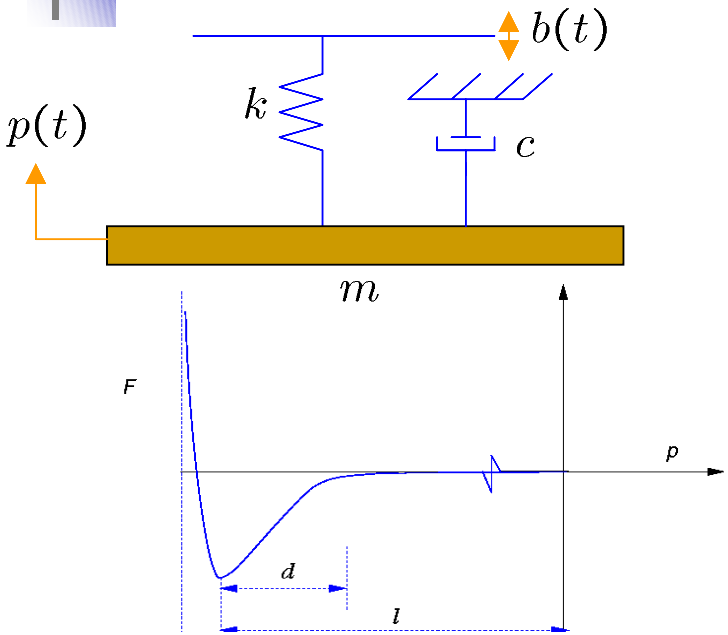


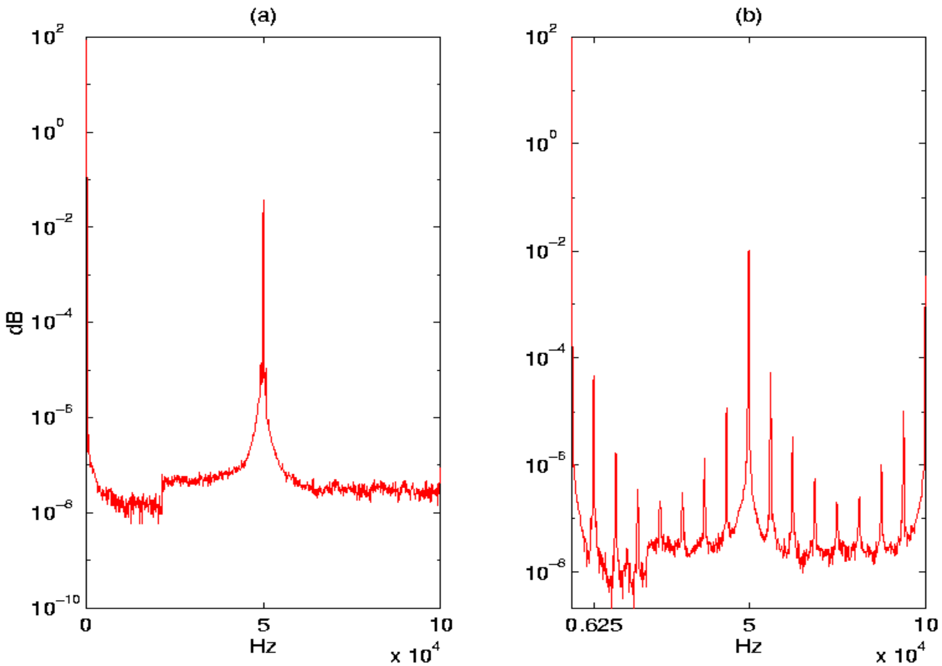


- Tip sample interaction force: long range attractive and short range strong repulsive force
- Lennard-Jones potential a representative of the tip-sample interaction
- The unforced dynamics has a homoclinic orbit which under the sinusoidal forcing separates into stable and unstable manifolds.

Joint work with Ashhab, Mezic and Dahleh
Ref (1). "Melnikov-based dynamical analysis of microcantilevers in scanning probe microscopy", *Nonlinear Dynamics*.;
Ref (2). "Dynamical analysis and control of micro-cantilevers", *Automatica,*

COMPLEX DYNAMICS

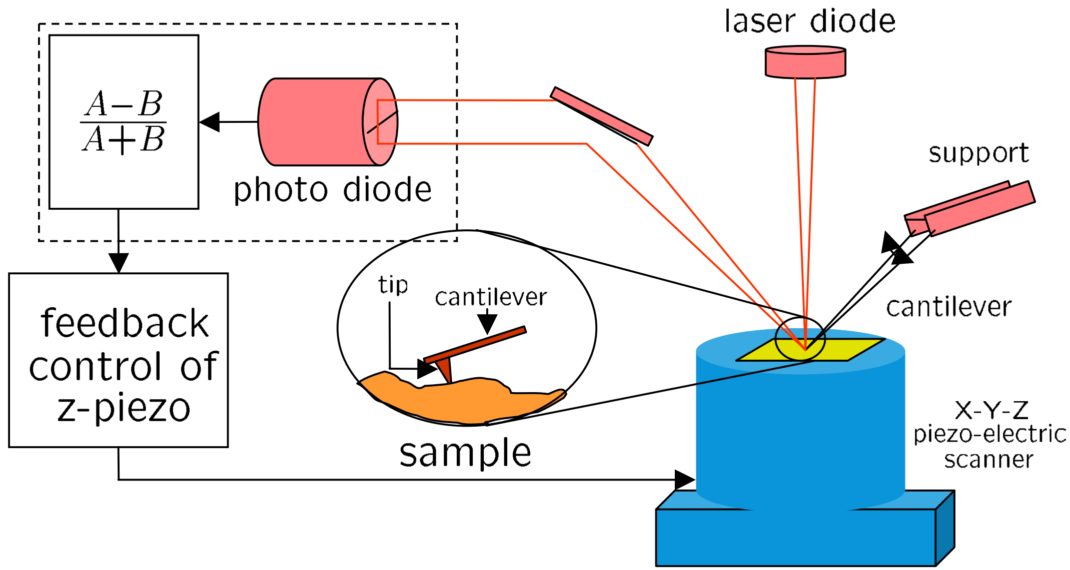




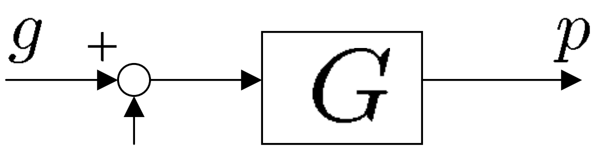
- It can be shown (using the Melnikov function) that for the appropriate parameter region these manifolds intersect
- Conley Moser conditions can be used to deduce complex dynamics
- Experiments conducted demonstrate such rich behaviour

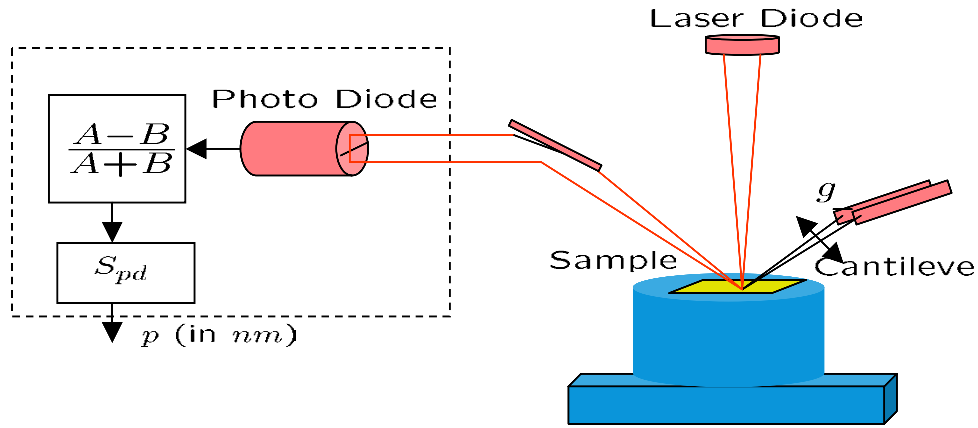
Ref. On the Dynamics of a Harmonic Oscillator Undergoing Impacts with a Vibrating Platform Work by Srinivasa Salapaka, Igor Mezic and Mohammed Dahleh

TAPPING MODE



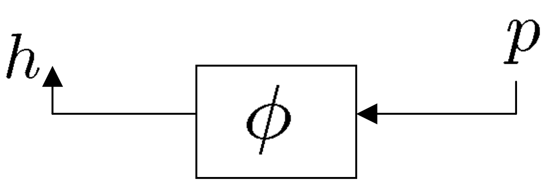
- In a wide range of operating conditions the sinusoidally forced cantilever evolves into a near sinusoidal orbit.





Cantilever system

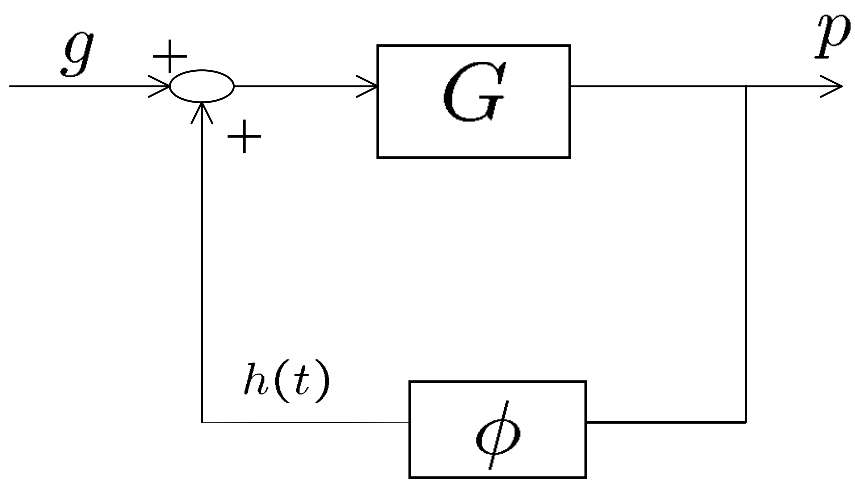
- Treat the cantilever as one system
  - Input = forcing (g) + sample force
  - Output = tip deflection



- Treat the sample as another system
  - Input is tip deflection
  - Output is the sample force

Sample system

Cantilever a Low Pass Filter



- G is assumed to be linear and can be identified precisely (thermal noise based). It has sharp bandpass characteristics about ω_0.
- ϕ corresponds to the tip-sample interaction which is nonlinear (assumed time invariant)
- G filters the higher harmonics of the signal $h(t) = \phi(p(t))$. Thus a near sinusoidal orbit.

Existence/Stability of Per. Solns.

- Define

$$\Pi(\eta) = \begin{pmatrix} 0 & j\omega\eta + k \\ j\omega\eta + k & -2 \end{pmatrix}$$

- $\exists\epsilon > 0$ such that

$$\begin{pmatrix} (j\omega I - A)^{-1}B \\ I \end{pmatrix}^* \tilde{\Pi}(jw) \begin{pmatrix} (j\omega I - A)^{-1}B \\ I \end{pmatrix} \leq \; -\epsilon I \text{ for all } \omega \in R$$

where $\tilde{\Pi} = \begin{pmatrix} C^T\Pi_{11}C & C^T\Pi_{12} \\ \Pi_{21}C & \Pi_{22} \end{pmatrix}$

- If the IQC defined by $\Pi(0)$ is satisfied by ϕ there exists a T periodic solution that is globally asymptotically stable. (Circle Condition)

- If $\exists$, $\eta \in R$ such that $\Pi(\eta)$, IQC is satisfied by ϕ then there exists a T periodic solution. (Popov Condition)

Ref. Work by Abu Sebastian; Follows from work by Yakubovic, Rantzer, Megretski

BOUNDS ON HIGHER HARMONICS

If,

- ϕ satisfies the IQC defined by Π
- $\begin{pmatrix} G(jk\omega_0) \\ 1 \end{pmatrix}^* \Pi(jk\omega_0) \begin{pmatrix} G(jk\omega_0) \\ 1 \end{pmatrix} \leq -\epsilon$ for all $|k| \neq 1$.

Then for $|k_0| \neq 1$, the bound $|p_{k_0}| < \beta |g_1|$ holds for all β that together with some $\tau > 0$ satisfies the inequality

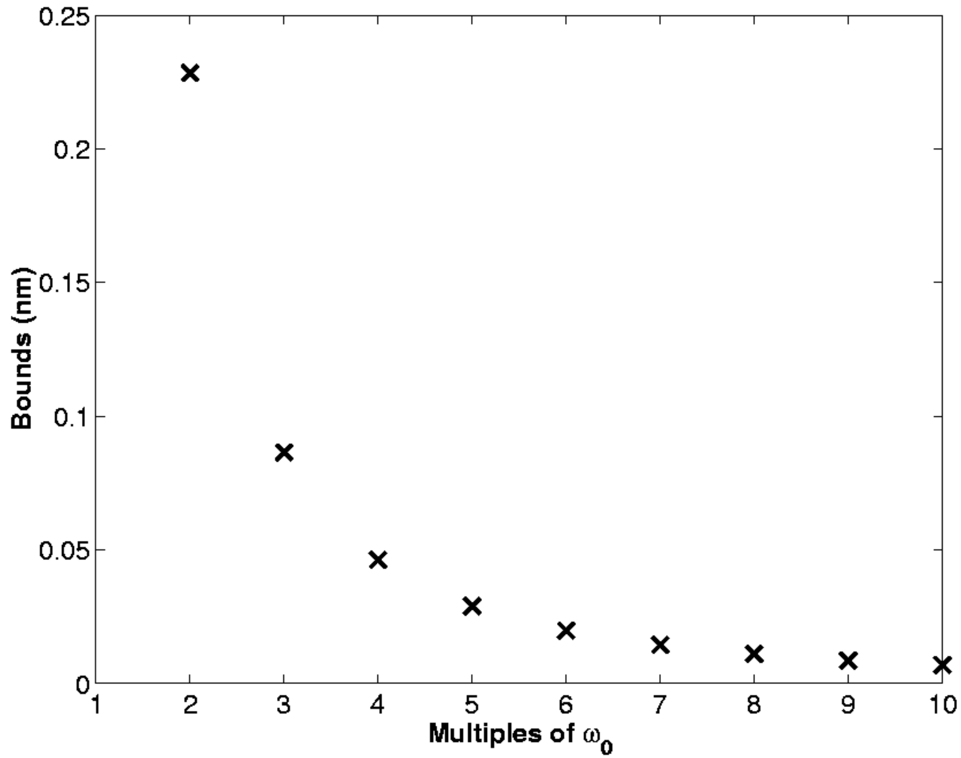
$$0 > \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\beta^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \tau \begin{pmatrix} K_1 & L_1 & 0 \\ L_1^* & M_1 & 0 \\ 0 & 0 & K_{k_0} \end{pmatrix} \qquad (1)$$

where $\begin{pmatrix} K_k & L_k \\ L_k^* & M_k \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ G^{-1}(jk\omega_0) & -1 \end{pmatrix}^* \Pi(jk\omega_0) \begin{pmatrix} 1 & 0 \\ G^{-1}(jk\omega_0) & -1 \end{pmatrix}$

Ref. Follows from work by Rantzer, Megretski

A Priori Bounds on Harmonics

Obtained using the Popov IQC

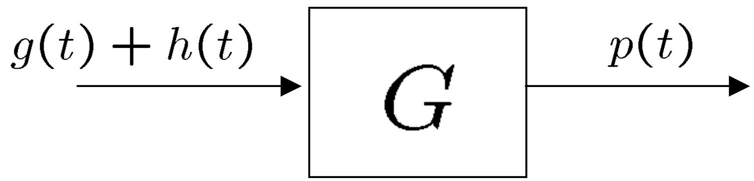


- Higher Harmonics very small compared to the free oscillation amplitude of $\approx 24nm$

- Useful for studying limitations.

Work by Abu Sebastian

Harmonic Balance

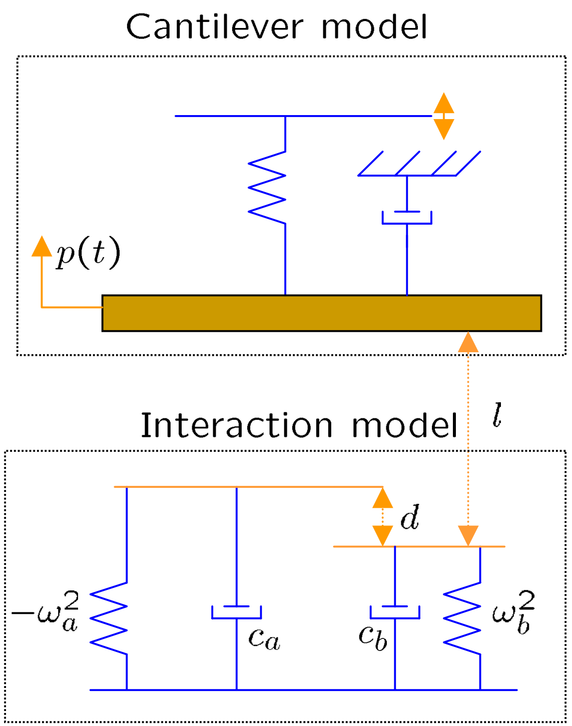


- $G(j\omega)(g_k + h_k) = p_k$
- Because of the near-sinusoidal nature of $p(t)$ the Harmonic balance equations reduce to:

$$\begin{aligned} G(0)(g_0 + h_0) &= p_0 \\ G(j\omega)(g_1 + h_1) &= p_1 \end{aligned}$$

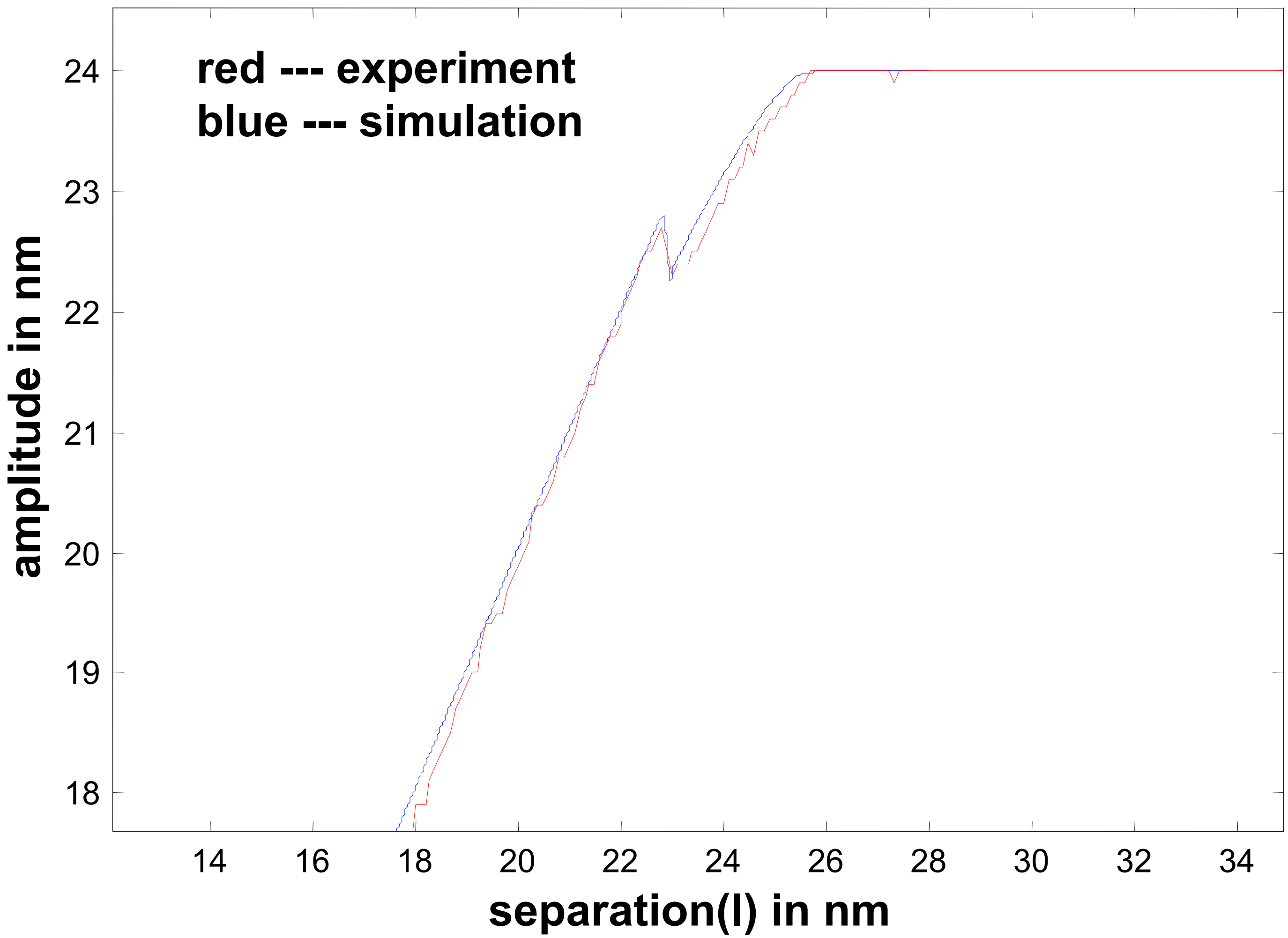
IDENTIFICATION: HARMONIC BALANCE

- From the interaction model $h_0(a, \phi)$ and $h_1(a, \phi)$ are obtained as closed form functions of model parameters (linear in the parameters)
- From the harmonic balance equations h_0 and h_1 can be evaluated from experimentally obtained $p(t)$ at different points of separation (l)

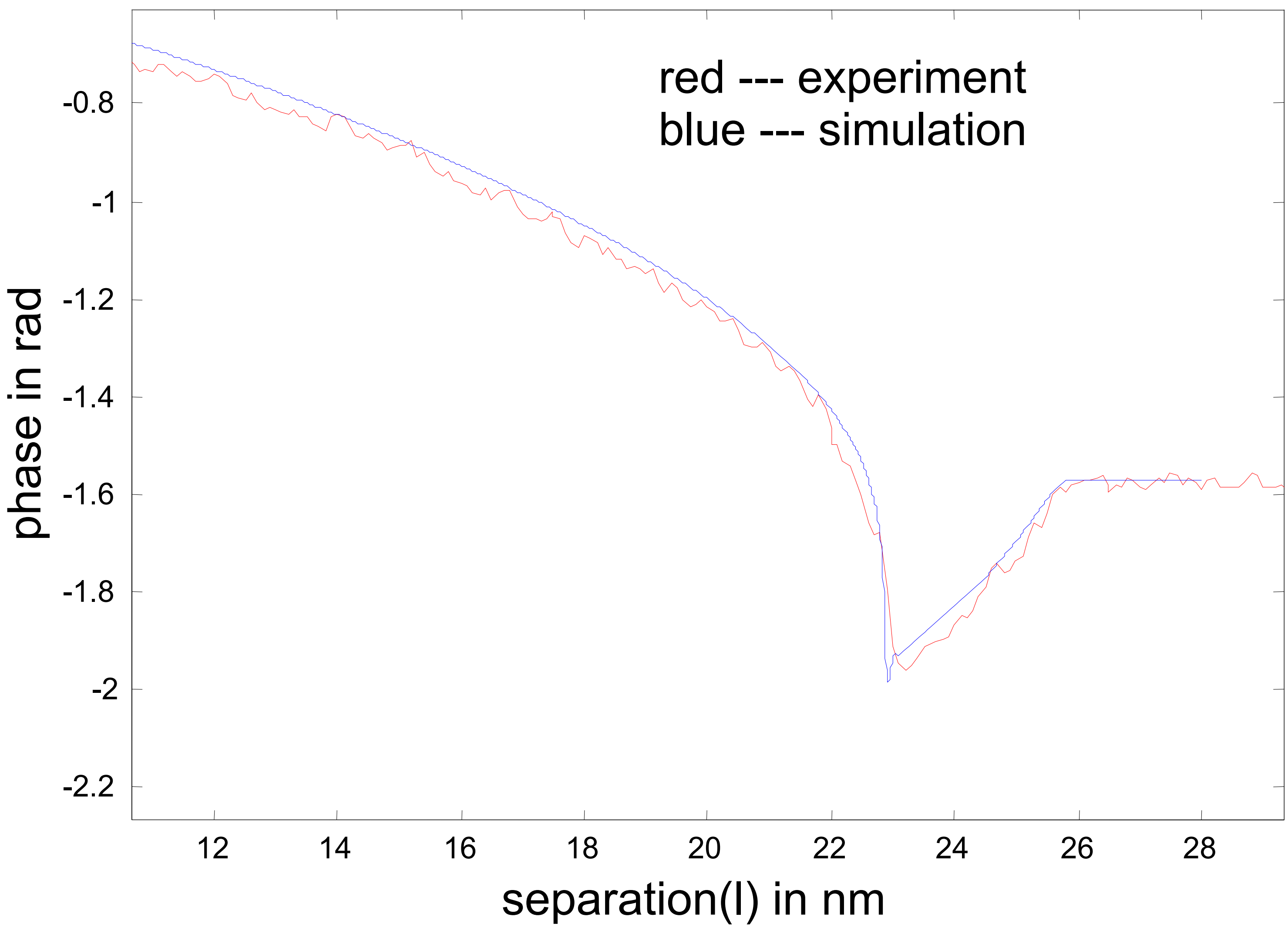


Ref. A. Sebastian, M. V. Salapaka, D. Chen, and J. P. Cleveland, "Harmonic and power balance tools for tapping-mode atomic force microscope", *Journal of Applied Physics*, June, 2001.

AMPL. VS SEPARATION



PHASE VS. SEPARATION



Summary

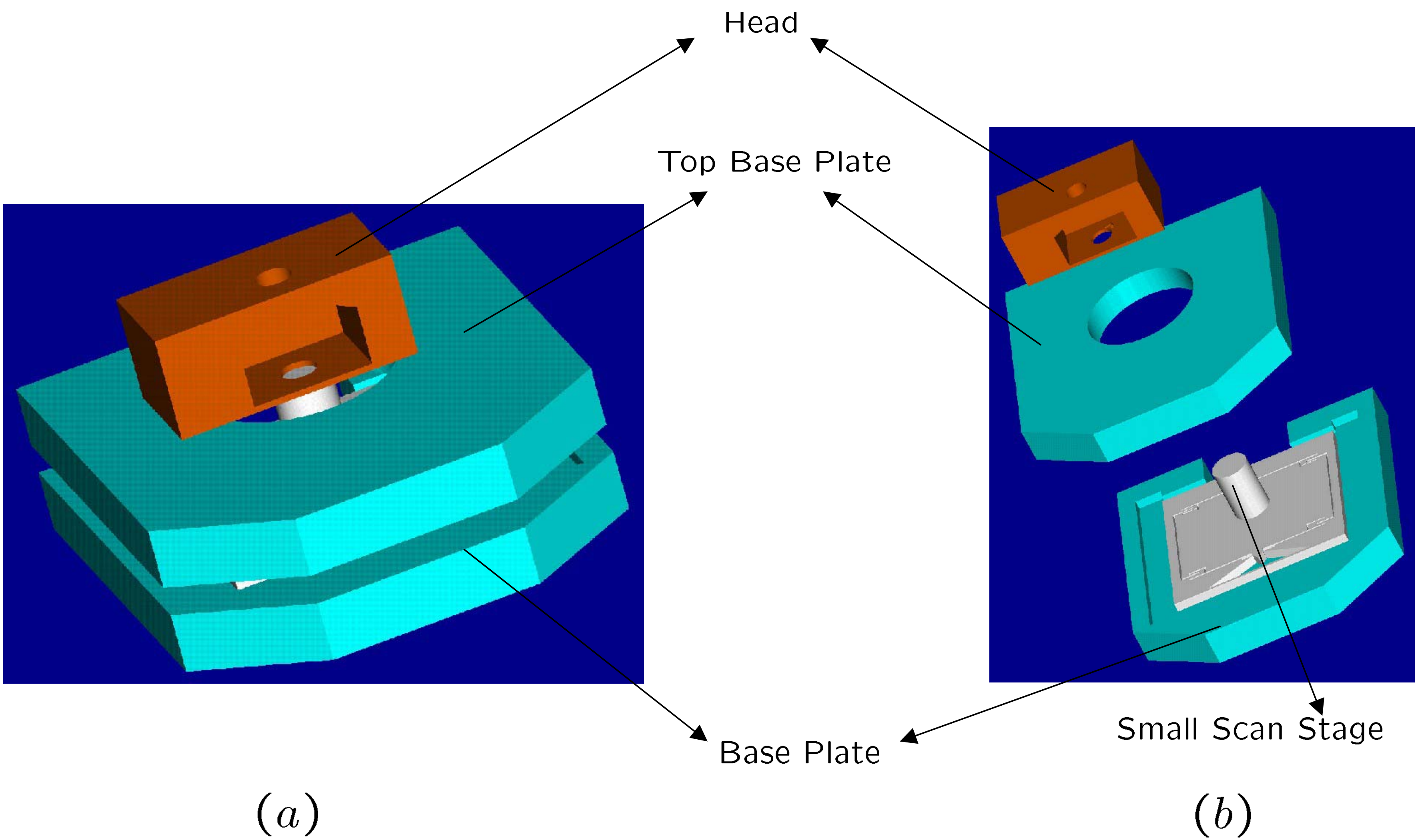
- Using the above principles one can identify the equivalent attractive stiffness, repulsive stiffness of various materials at the nanoscale

- The harmonic bounds provide a means of evaluating limitations on how well sample characteristics can be identified

- The systems viewpoint provides new methods of imaging; Transient Force Imaging

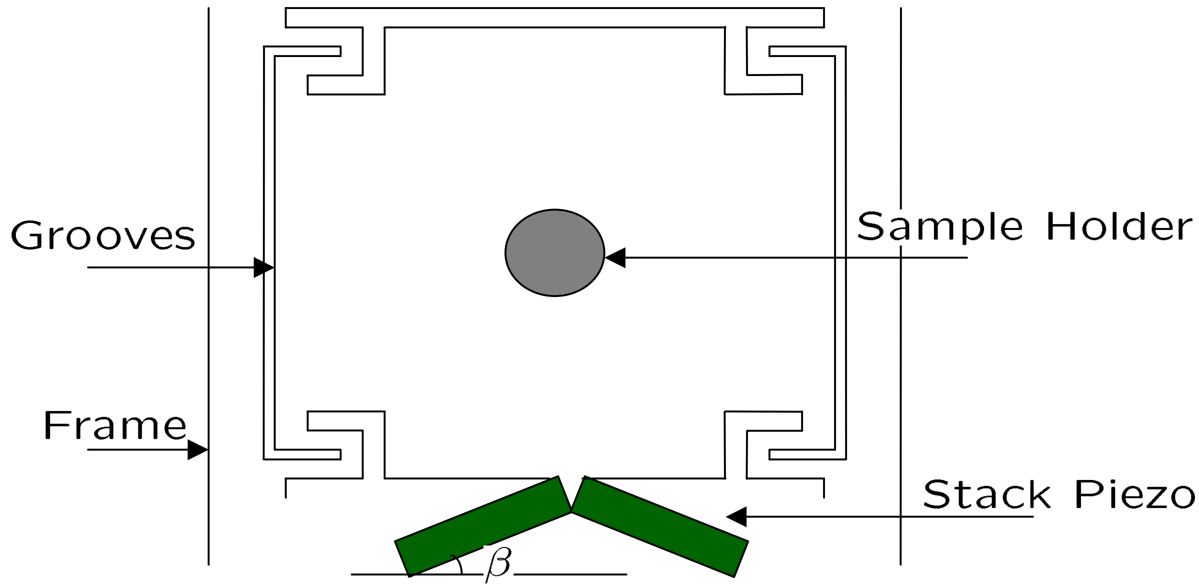
NanoPositioning

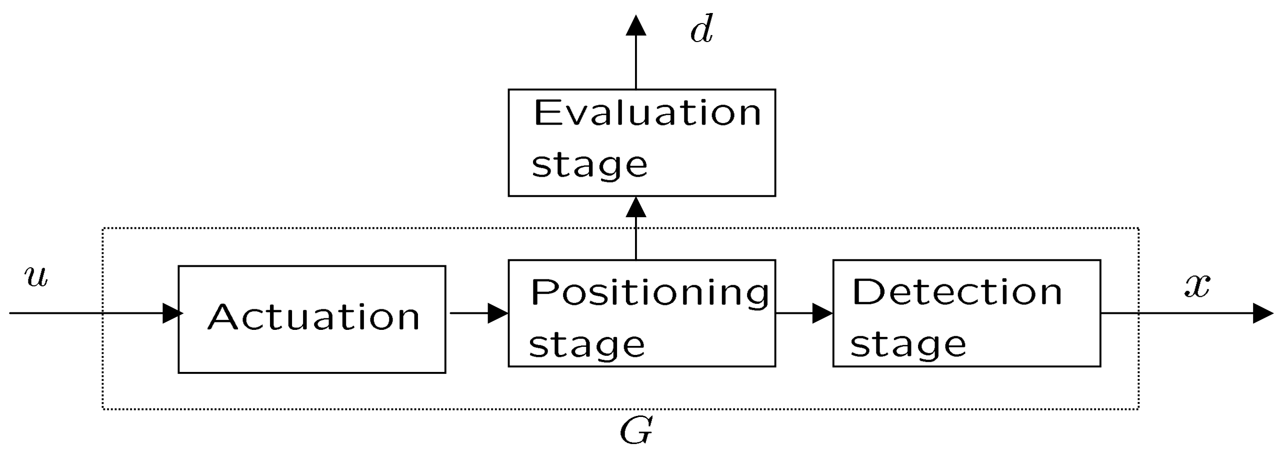
New Microscope



Work by Srinivasa Salapaka. and Abu Sebastian.

FLEXURE SYSTEM





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IDENTIFICATION

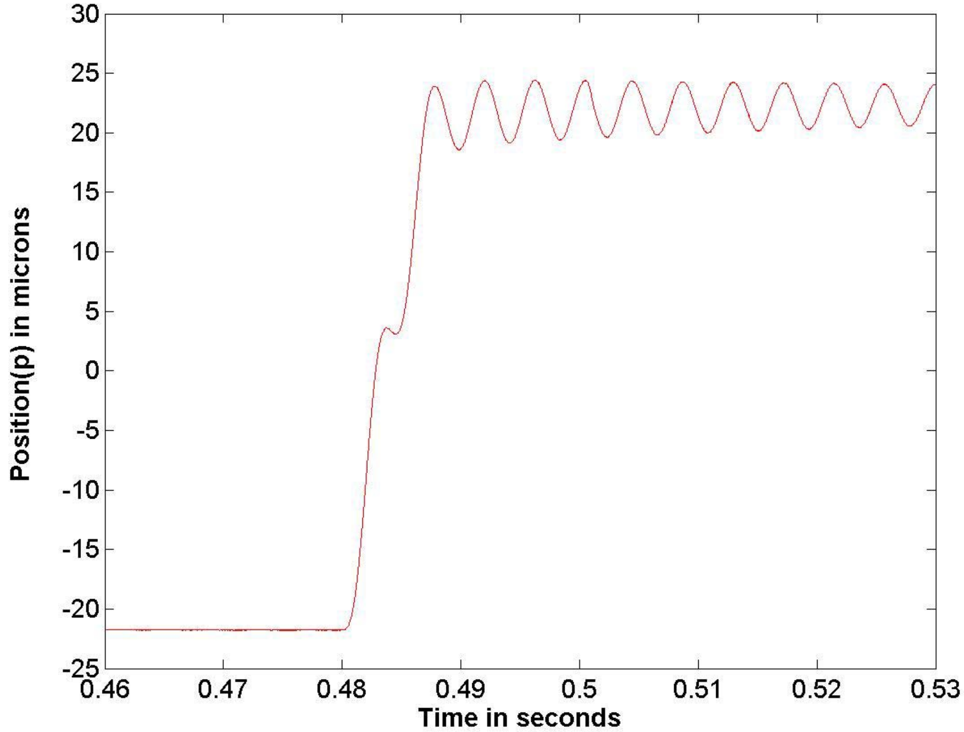
- There is considerable change in the frequency responses with varying operating conditions
- The response obtained about $x = 0$ is chosen as the nominal response
- A model G is obtained to fit the nominal response

$$G(s) = \frac{(s-[719.93+j736.16])(s-[719.93-j736.16])}{s^4+3753s^3+2.609\times10^7s^2+9.178\times10^9s+5.478\times10^{13}}$$

Work by Srinivasa Salapaka. and
Abu Sebastian.

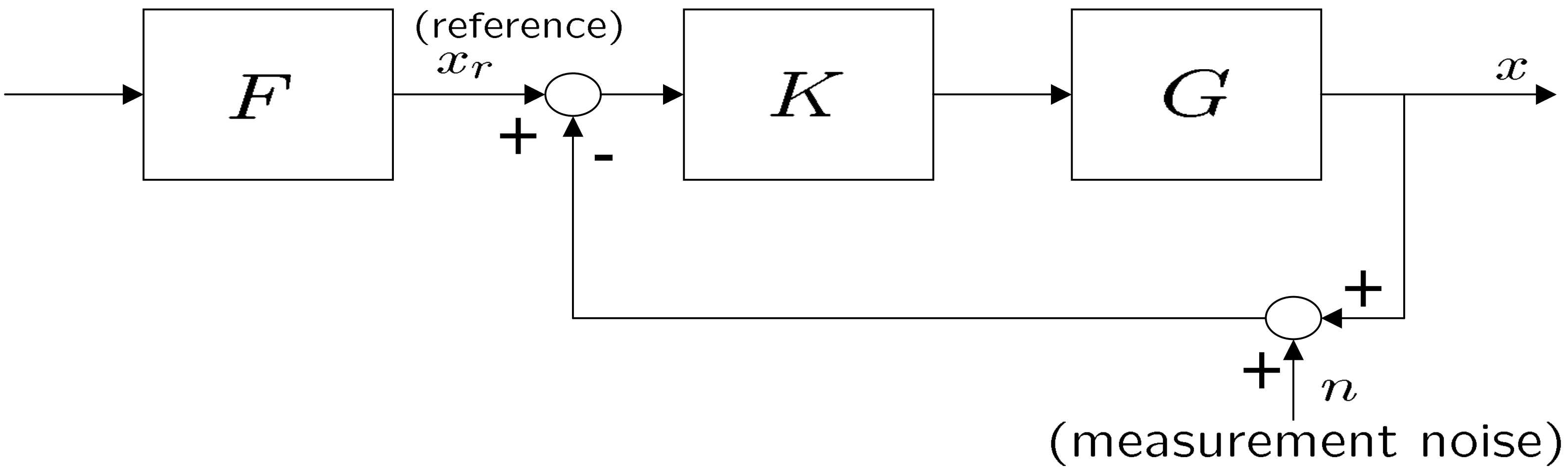
Step Response

Experimental step response



- Inverse response validates the presence of RHP zeros
- Performance often evaluated in terms of step response

SPECIFICATIONS



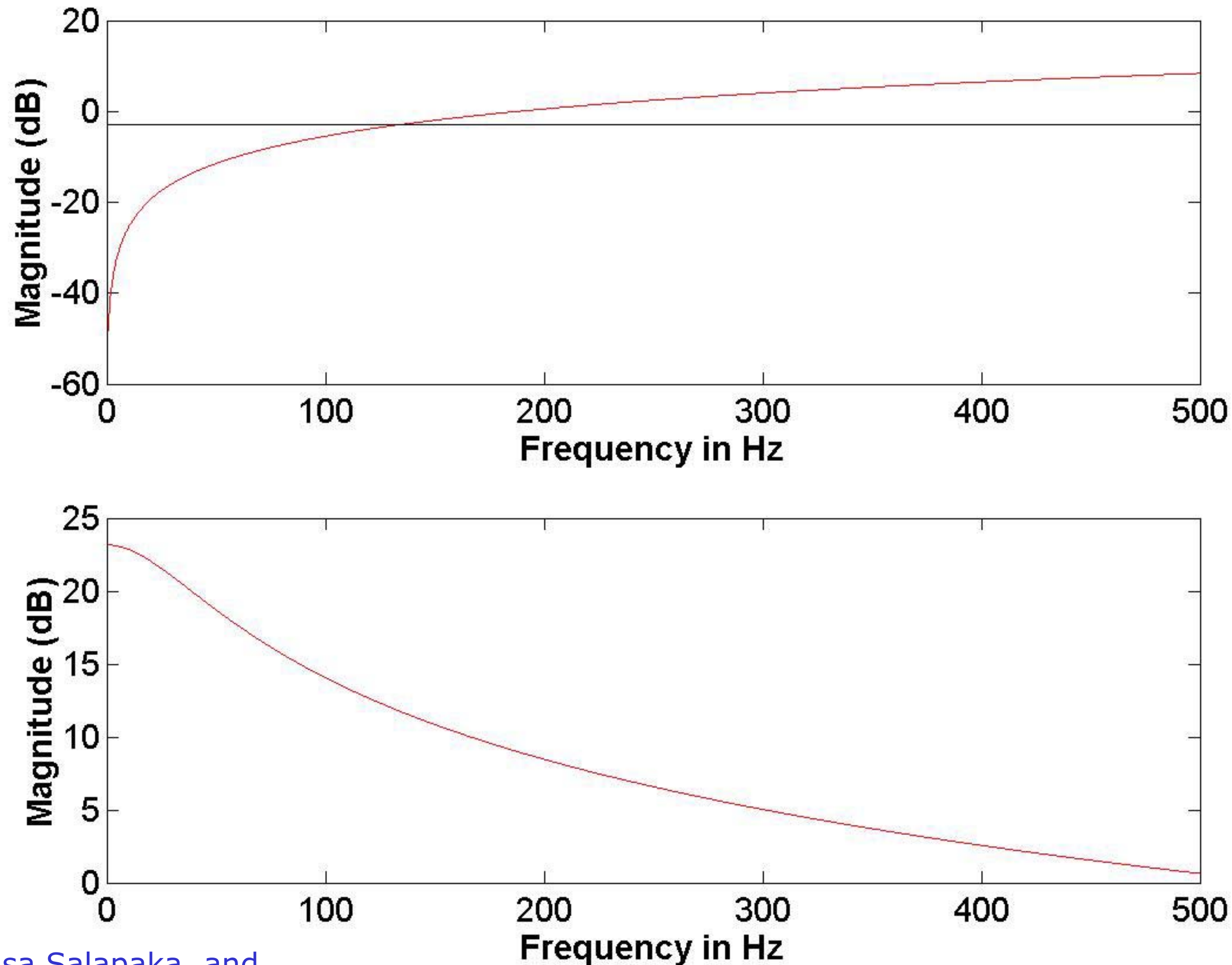
$e := x_r - x = Sx_r - Tn$

where $S := (1 + GK)^{-1}$, $T := (1 + GK)^{-1}GK$

T = Complimentary Sensitivity (transfer func. between e and n)

Work by Srinivasa Salapaka. and Abu Sebastian.

SPECS. ON SENSITIVITY FUNCS.



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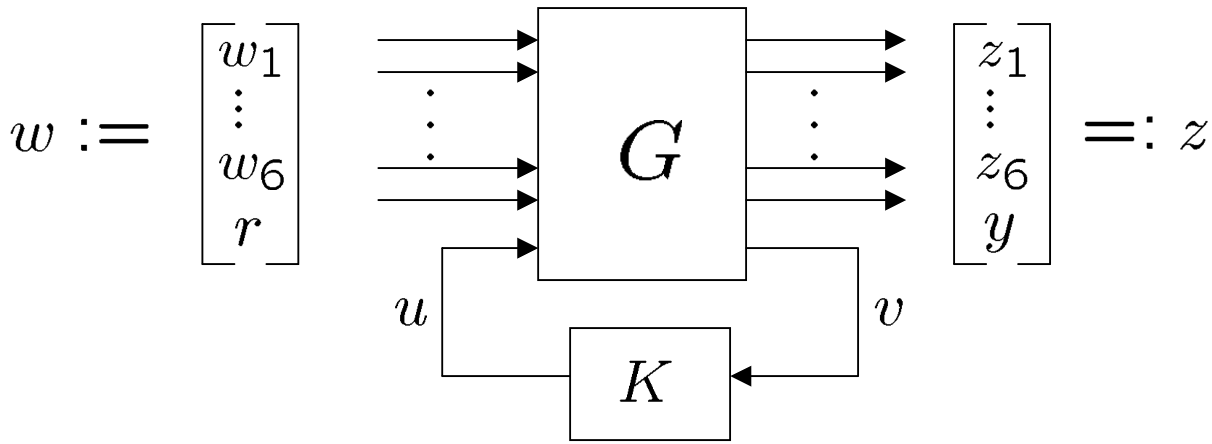
SATURATION

- Time Domain constraints
  - Control effort should not saturate
  - Step response should be within given specifications

- The variance of the output should be small due to the noise.

Multiobjective Control Theory



$$\inf \quad c_1 \|R^1(K)\|_1 + c_2 \|\hat{R}^2(K)\|_{\mathcal{H}_2}^2 + c_3 \|\hat{R}^3(K)\|_{\mathcal{H}_\infty}$$

K stabilizing

subject to

$$\|R^4(K)\|_1 \leq c_4$$

$$\|\hat{R}^5(K)\|_{\mathcal{H}_2}^2 \leq c_5$$

$$\|\hat{R}^6(K)\|_{\mathcal{H}_\infty} \leq c_6$$

$$a_{temp}(k) \leq y(k) \leq b_{temp}(k), \;\; k = 0, 1, 2, \ldots$$

Multiobjective Control

- Recent developments have lead to a computationally effective theory to address the problem.

Joint work with Xin Qi, Mohammed Dahleh, Mustafa Khammash, Petros Voulgaris,

PRESENT STATUS

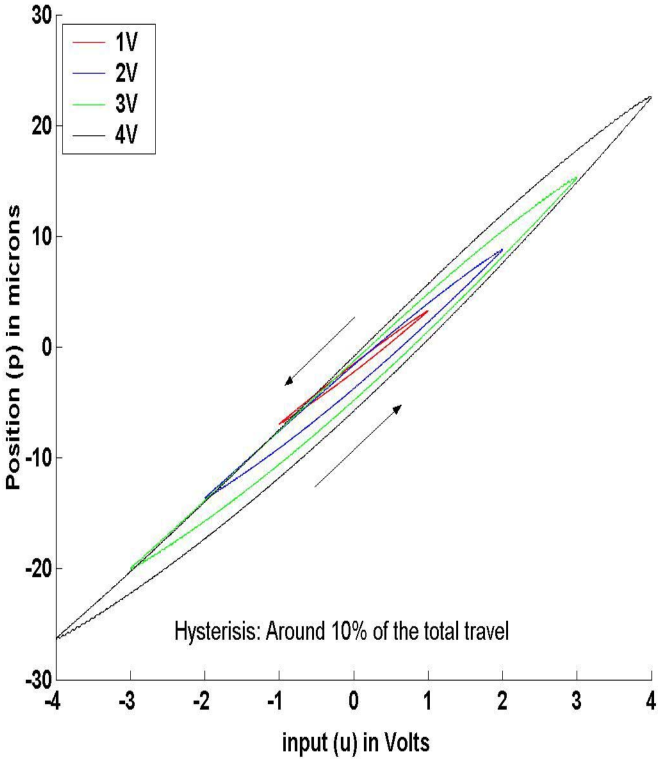
- The only controllers employed at present are PI controllers.

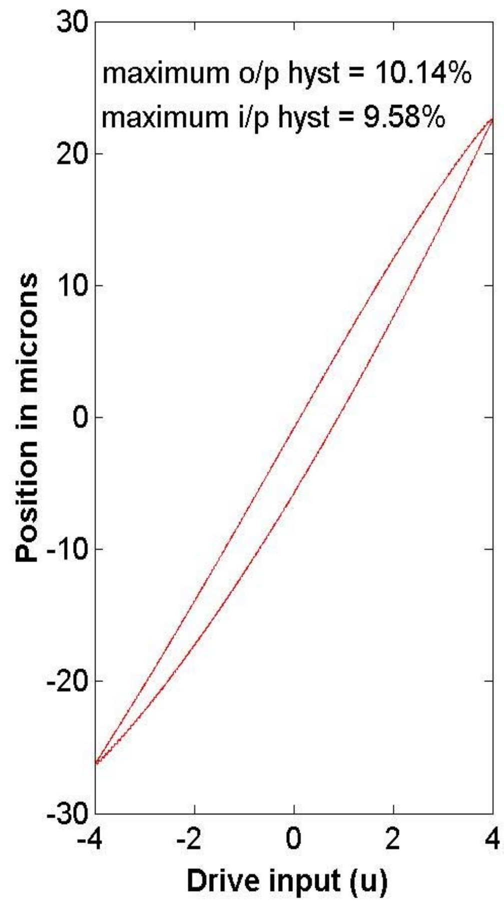
Work by Srinivasa Salapaka. and
Abu Sebastian.

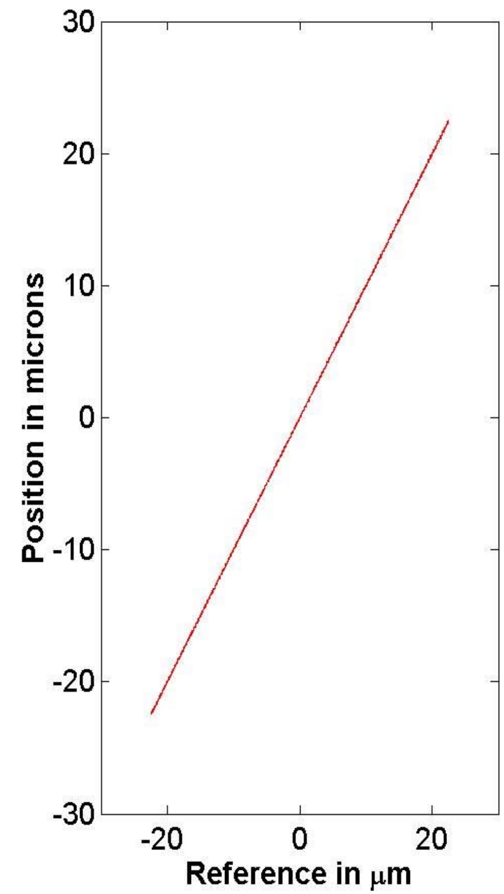
$\mathcal{H}_\infty$ DESIGN

Work by Srinivasa Salapaka. and
Abu Sebastian.

HYSTERESIS EFFECTS MINIMIZED



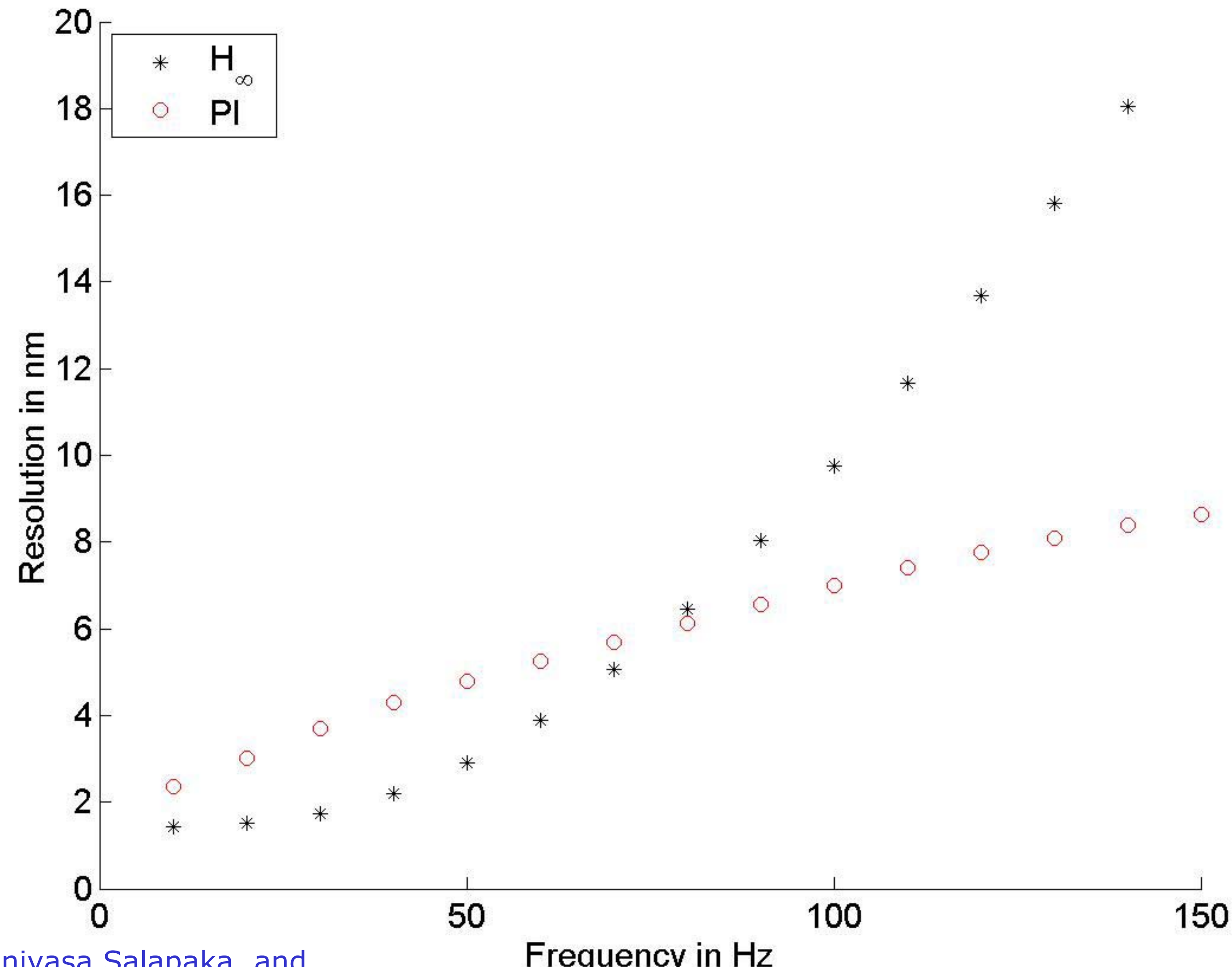




- Hysteresis effects in piezo material.
- Present work with Ralph Smith

Work by Srinivasa Salapaka. and Abu Sebastian.

POSITIONING RESOLUTION



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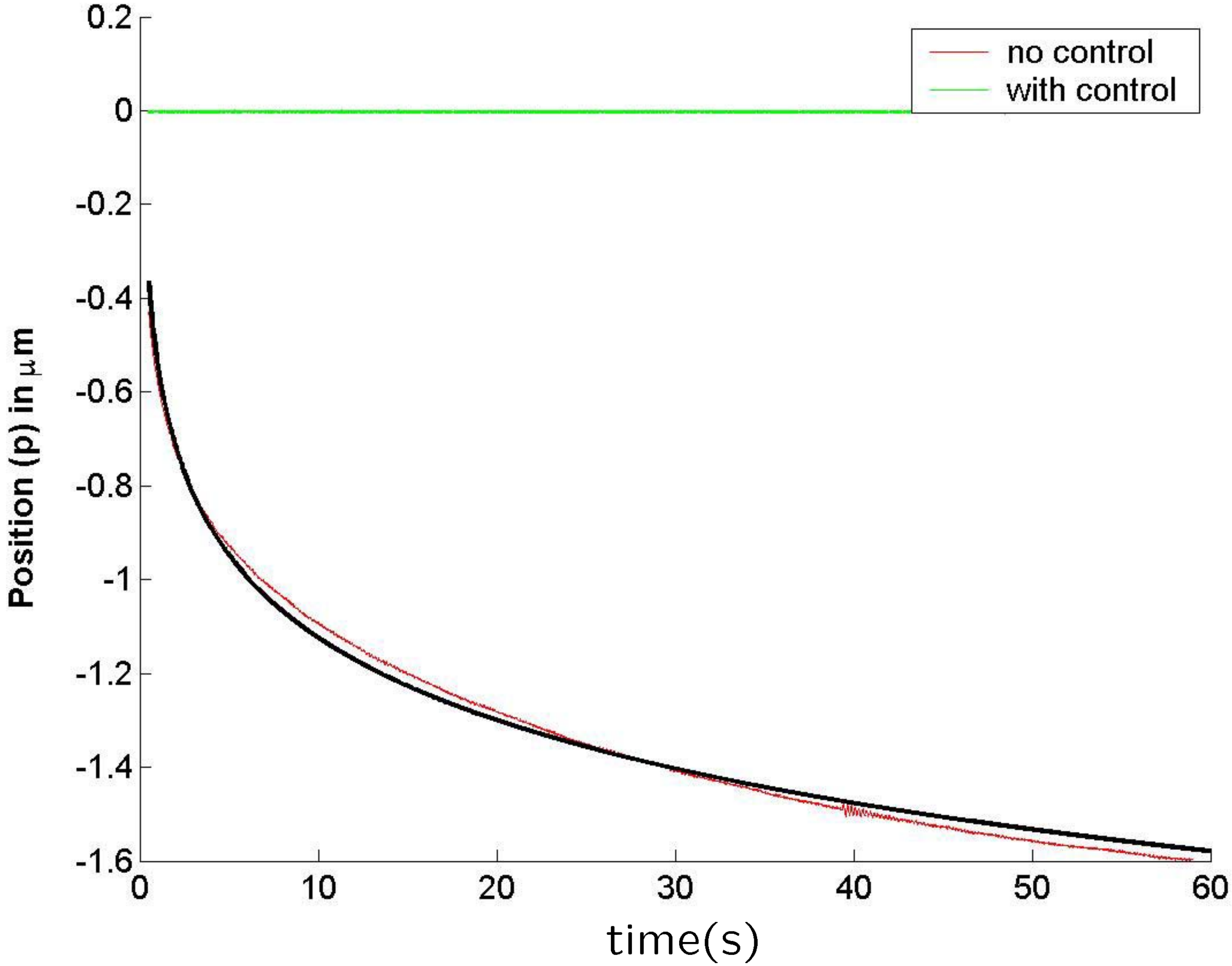
Creep Effects Minimized



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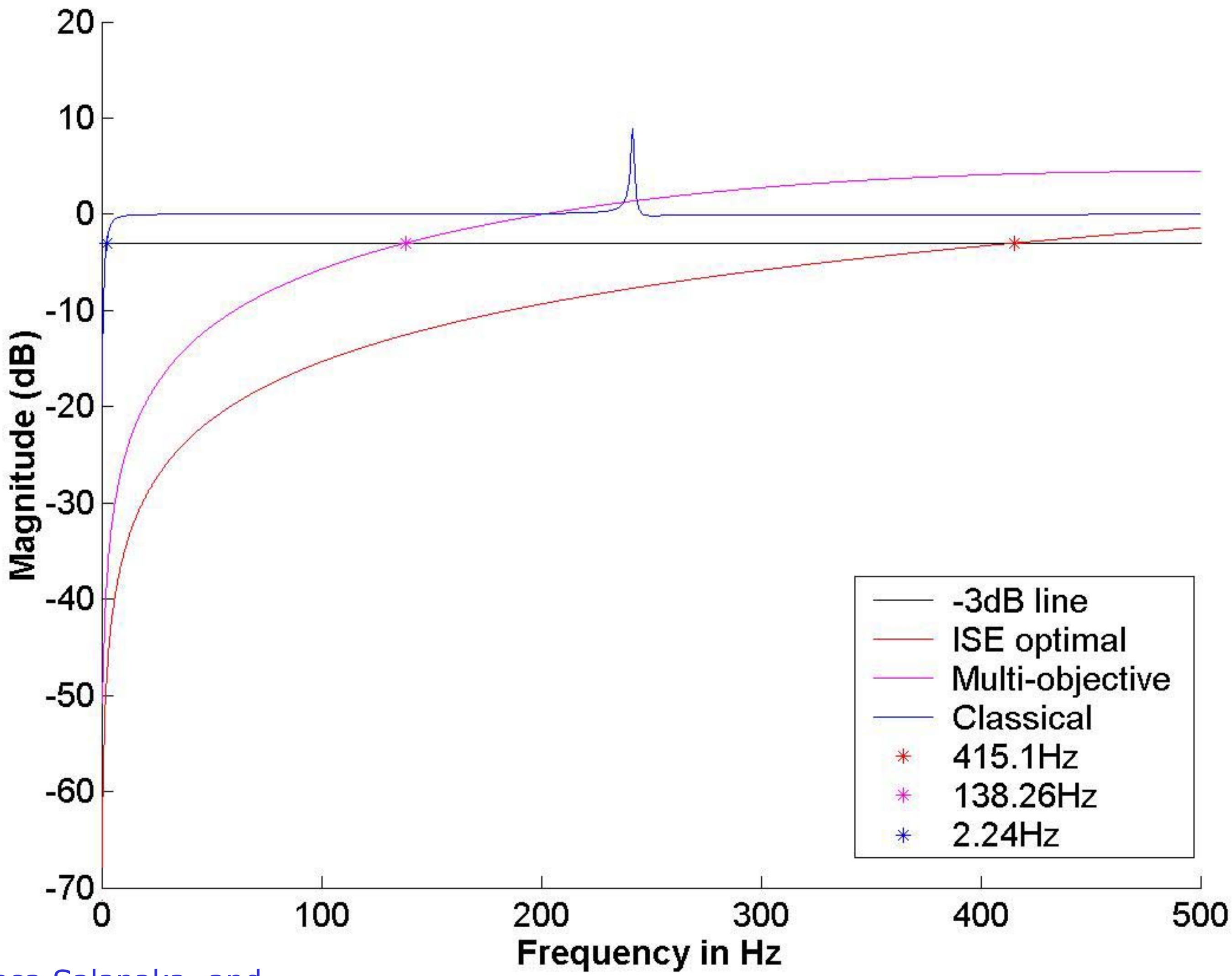
PI Vs $\mathcal{H}_\infty$ CONTROL



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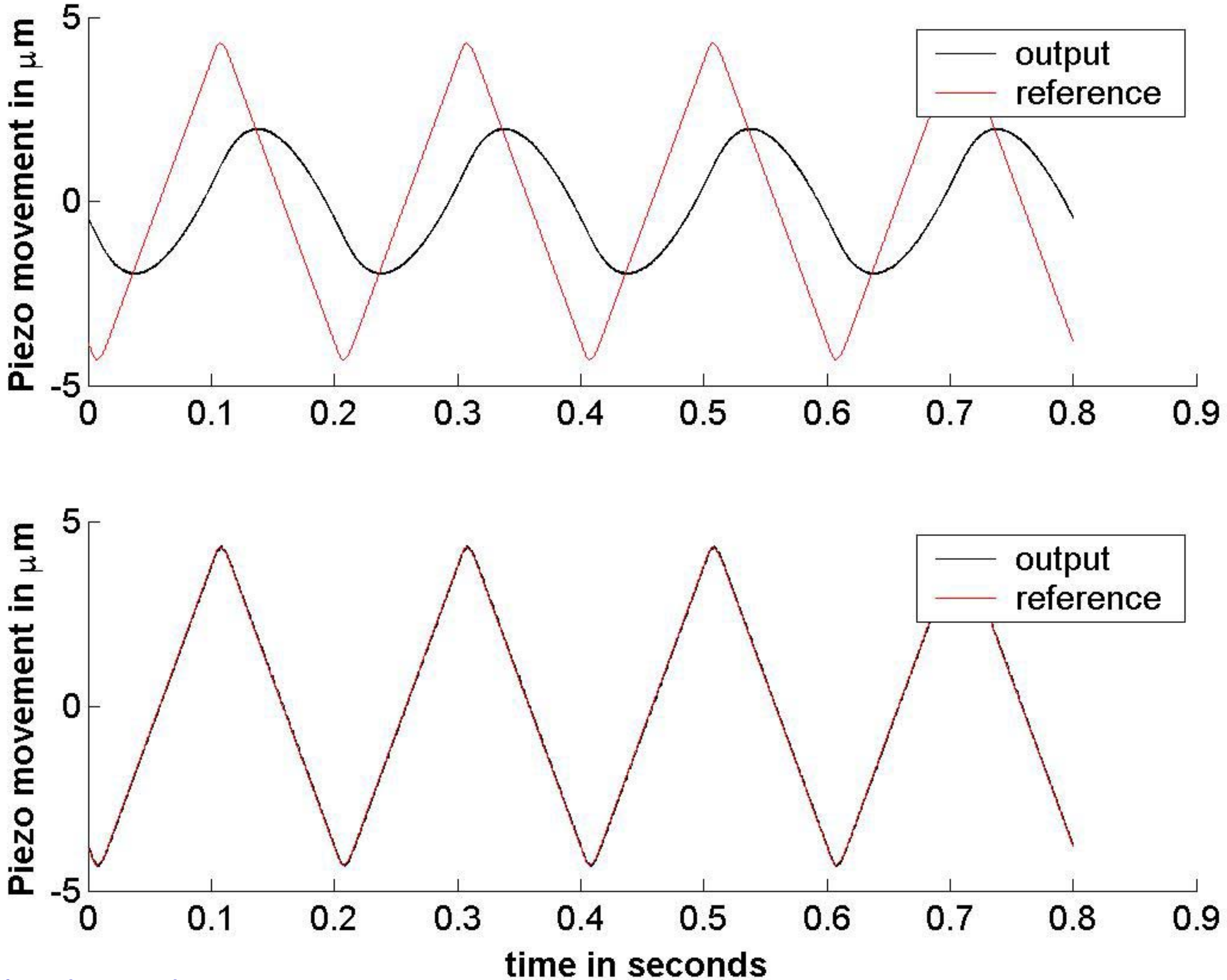
TRACKING TRIANGLE SIGNALS



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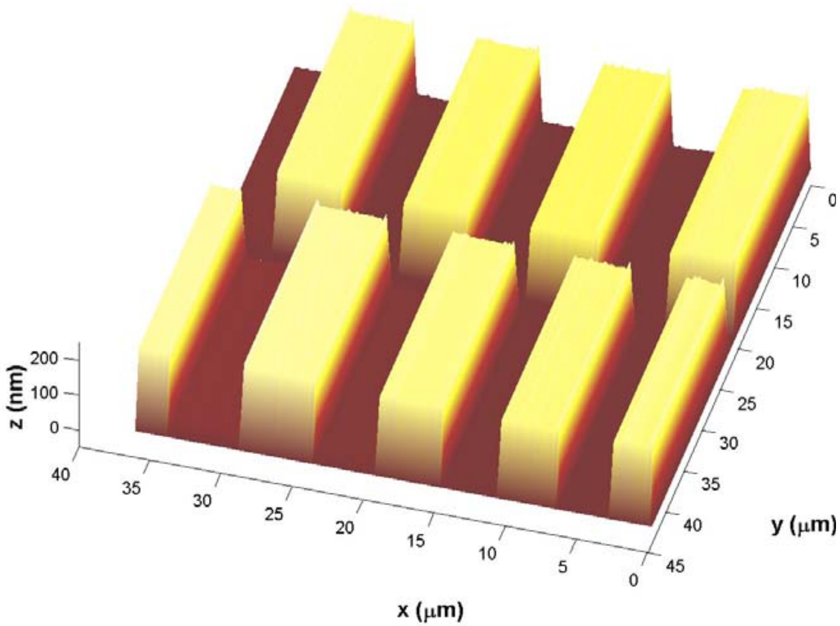
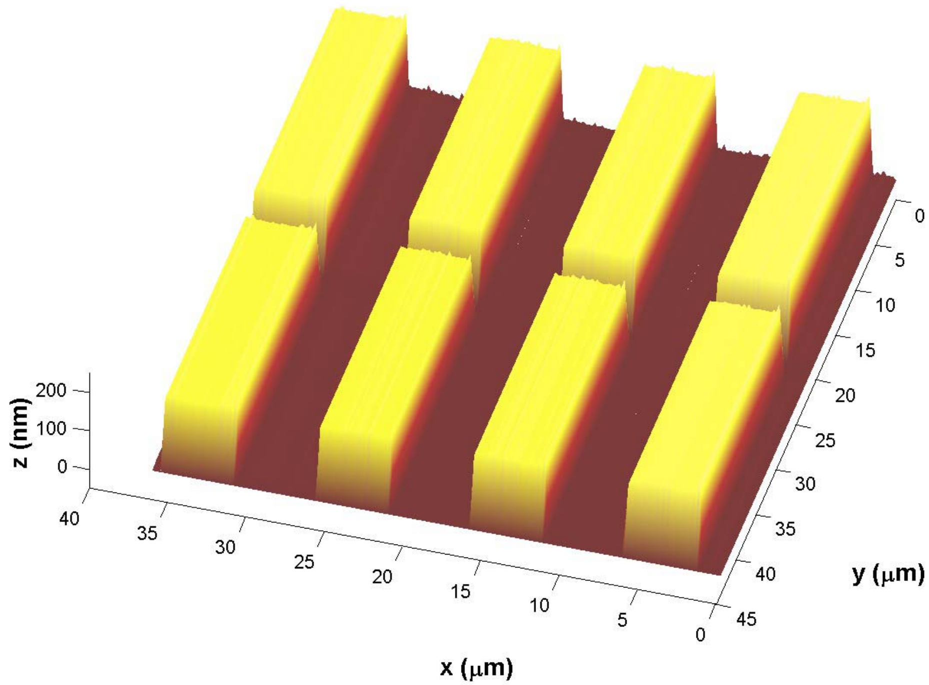
EXPERIMENTAL IMAGE





Work by Srinivasa Salapaka. and
Abu Sebastian.

SUMMARY

- Modern control and systems techniques have provided for considerably faster imaging and unique insights to the scanning probe literature.