UCSD

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Jacobs School *of* Engineering

# Identificatie & Regelaar Tuning:
# Een Stukje Hardheid op de Tafel

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On the occasion of Prof. Bosgra 65th birthday

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# What's up with the title?

**Translate text, webpage, or document**

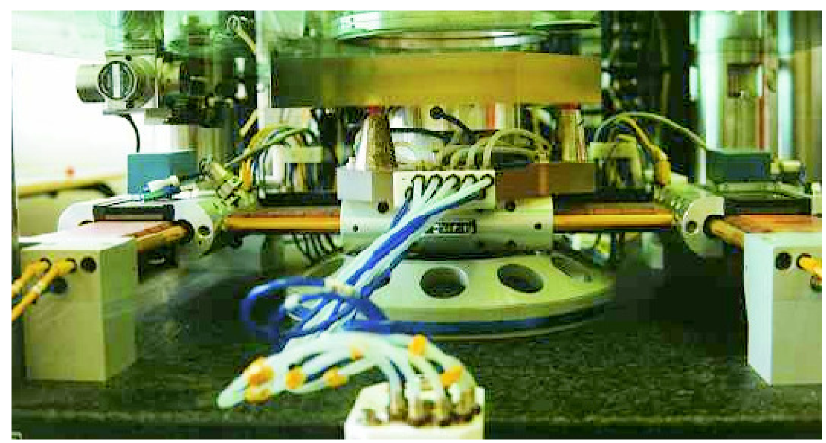
Enter text or a webpage URL, or upload a document.

```
Identificatie & Regelaar Tuning
Een Stukje Hardheid op de Tafel
```

Translation: Dutch » English

```
Identification and Controller Tuning
A Piece of hardness on the Table
```

- hardness = rigidity, solidity or just hard facts?
- From a PhD student's point of view:
  - Explain yourself in rigorous math
  - Show me your papers
  - I want to see how it works!
  - Where is your thesis?



another table…

# What's up with the title?

Frustration of not able to see any things on the table…

- Control: hidden technology
- Algorithms, Embedded, Integrated and Fed Back
- Name `control' itself is ambiguous (common & Kalman)
- A lot of research in many, many journals


- Bosgra: creating some order in the chaos!



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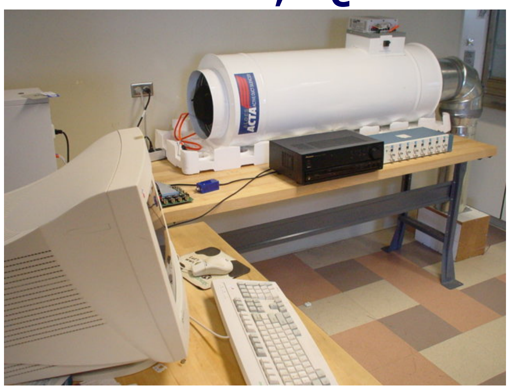
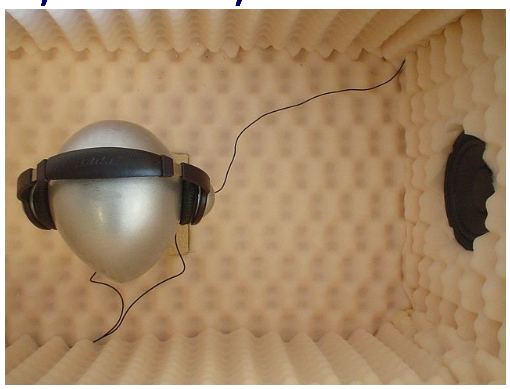
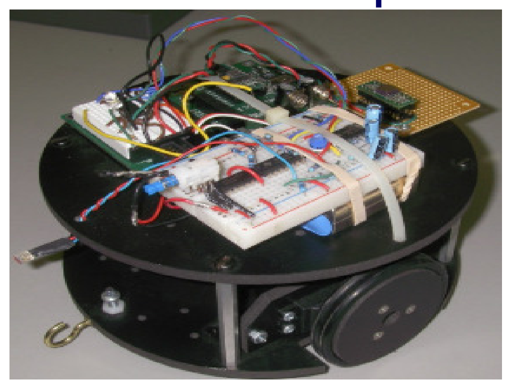
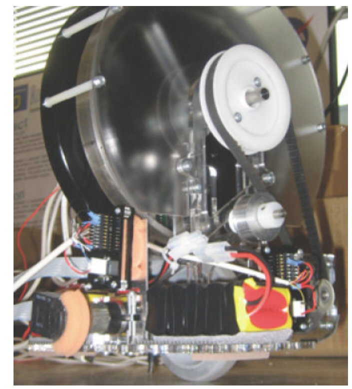
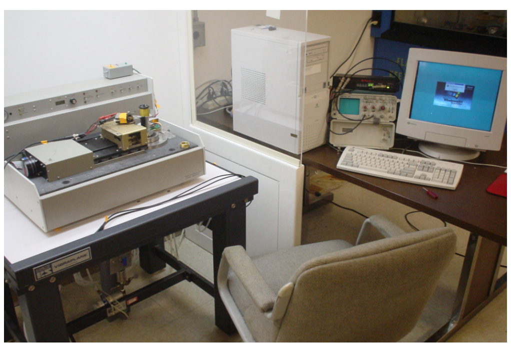
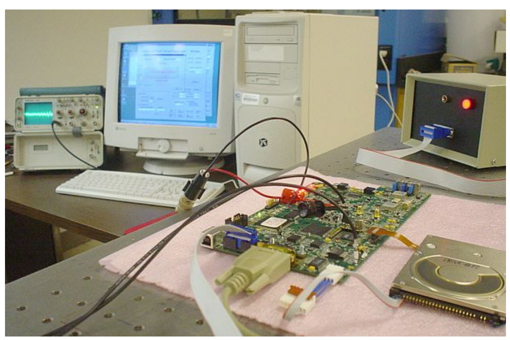
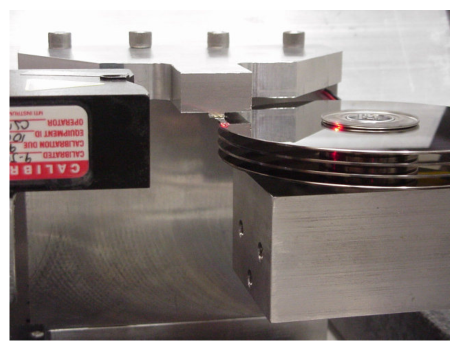
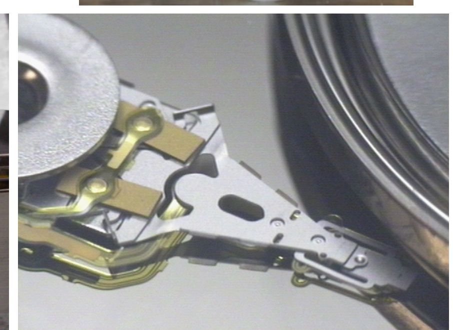
# Inspired by the Delft control background

- System identification, interaction between data-based modeling and control, identification of LPV systems, adaptive control, motion control.
- Applications include mechanical, servo, and structural systems, including data storage systems (hard disks and tapes) and active noise control.
- Industrial partners includes Seagate, Western Digital, Cymer, Hewlett-Packard, Quantum, Kodak, Vektrex and industrial sponsors via INSIC.

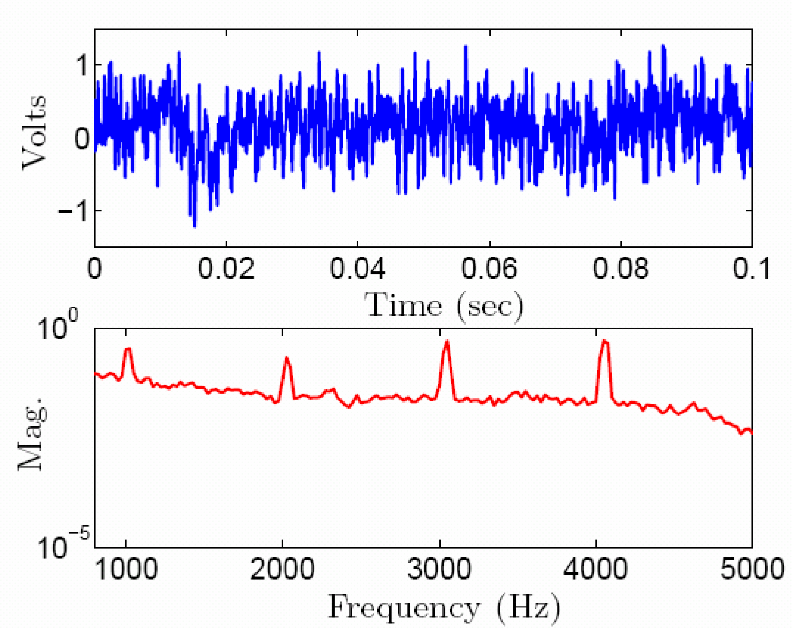









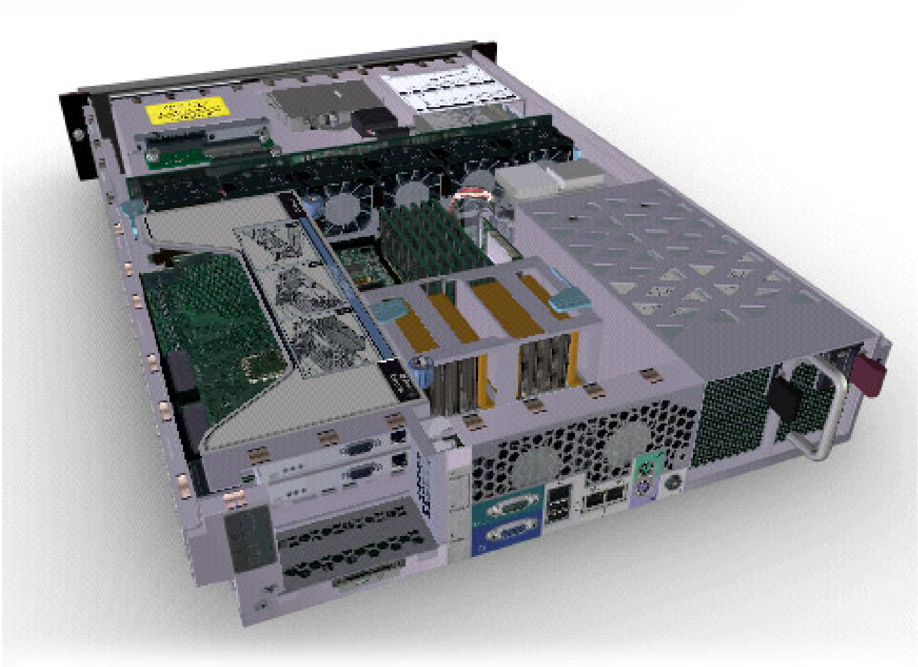
# Een Klein Stukje Hardheid op de Tafel:
# Robust Estimation for Automatic Control Tuning (REACT)

- Motivation & Illustration
- Some Details
  - Plant and Controller perturbation
  - Error signal
  - Variance minimization
  - Stability robustness
- Example & Application

# REACT – motivation

Application in Active Noise Control of Cooling Fans:

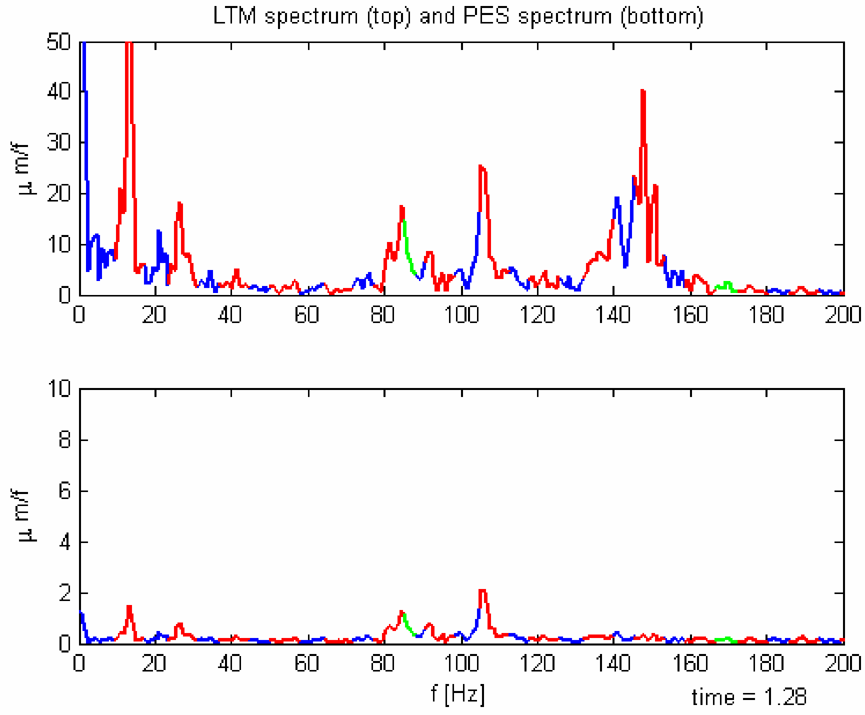


- Blade Pass Frequency (BPF) cause harmonic sound disturbances, along with non-periodic airflow noise
- Speed of fan and BPF not known and vary over time
- HP and Dell especially interested in Active Sound Compensation (ASC) of BPF and `beating' phenomena

# REACT – motivation

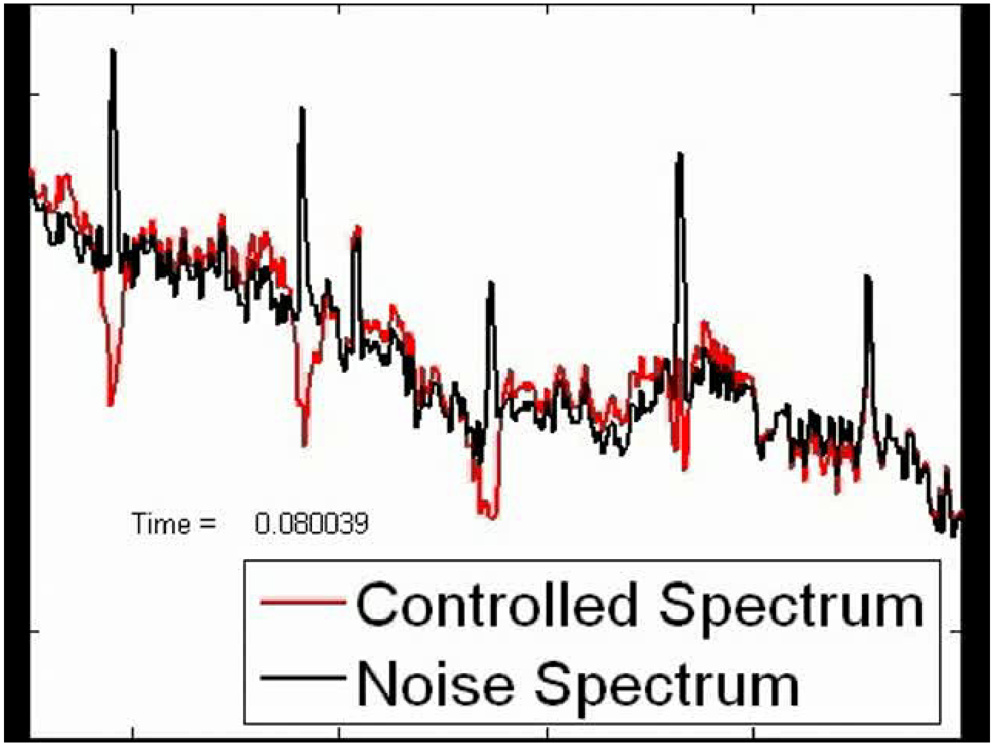
Application in High Density Tape Storage (1/2 height LTO drive):




- Rotation of cartridge reel cause periodic disturbances
- Reel diameter changes over time and tape runs at varying speeds
- Unknown non-periodic disturbance spectra

# REACT – illustration

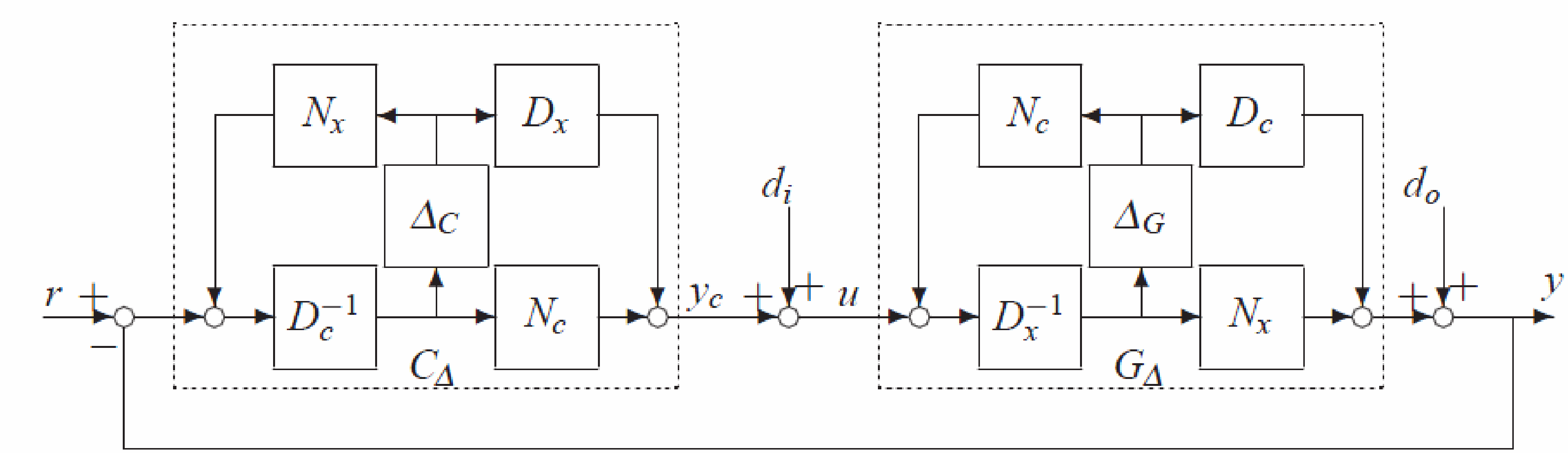
Demonstration of REACT:




- Double fan contained in box with control baffle that contains speakers and microphones in feedback configuration
- Adaptive tuning of servo controller to cancel harmonics

# REACT – plant perturbation

Consider simultaneous Plant and Controller perturbation in Youla parametrization:




Plant:

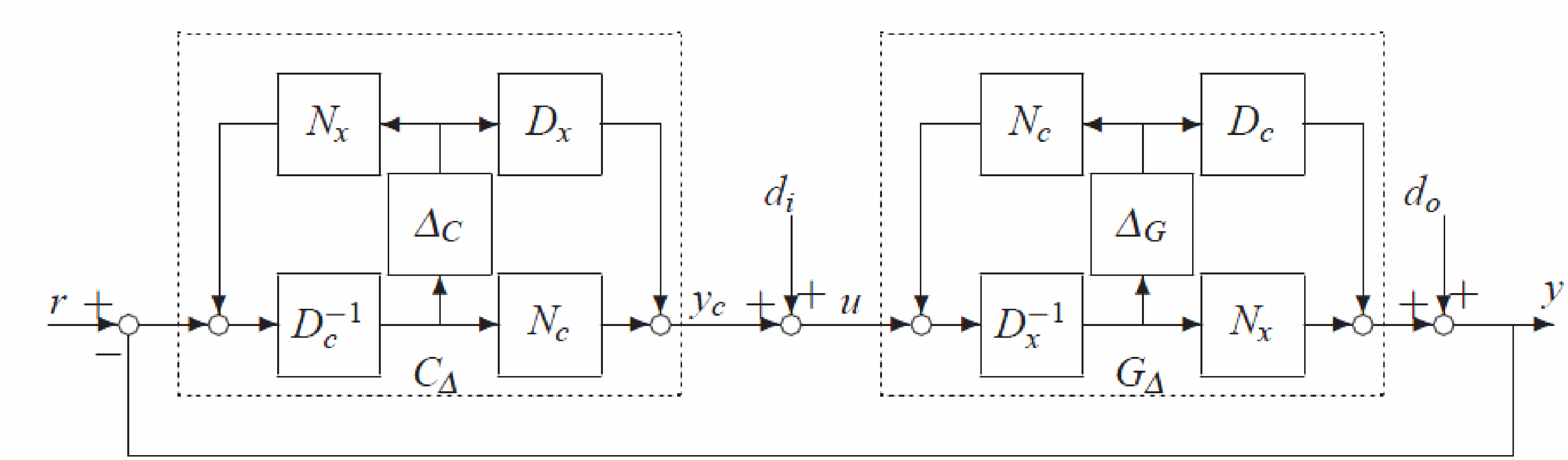
$$G_\Delta = N_{G_\Delta} D_{G_\Delta}^{-1} = (N_x + D_c \Delta_G)(D_x - N_c \Delta_G)^{-1}$$

$$\Xi = \{\Delta : \|\Delta\|_\infty < 1/\gamma,\ \Delta \in \mathcal{RH}_\infty\}$$

$$\Pi = \{P : P = (N_x + D_c \Delta_G)(D_x - N_c \Delta_G)^{-1}, \Delta_G \in \Xi\}$$

# REACT – control perturbation

Consider simultaneous Plant and Controller perturbation in Youla parametrization:




Controller: $C_\Delta = N_{C_\Delta} D_{C_\Delta}^{-1} = (N_C + D_x\Delta_C)(D_C - N_x\Delta_C)^{-1}$

$$\Delta_C[u(t)] = \Theta(t)^T \int_0^t (C_D e^{A_D(t-\tau)} B_D + D_D) u(\tau) d\tau$$

$$= \Theta(t)^T (\mathscr{D}(t) * u(t)), \quad \mathscr{D}^T = \left[ \mathrm{I}\left(\frac{s-p_0}{s+p_0}\right) \ \mathrm{I}\left(\frac{s-p_0}{s+p_0}\right)^2 \ \ldots \ \mathrm{I}\left(\frac{s-p_0}{s+p_0}\right)^{n_\theta} \right]$$

# REACT – error signal

At this point, we will introduce two parameters: θ and Ψ

- Needed to separate optimization problem from control problem
- $\Delta_C(\theta)$: controller perturbation used in optimization
- $\Delta_C(\Psi)$: controller perturbation used in feedback

Benefit from Youla parametrization and parameter separation:

$$\begin{aligned} y &= (I + G_\Delta C_\Delta)^{-1} d_o + G_\Delta (I + C_\Delta G_\Delta)^{-1} d_i \\ &= (I + G_\Delta C_\Delta)^{-1} d_o + (I + G_\Delta C_\Delta)^{-1} G_\Delta d_i \\ &= D_{C\Delta} \tilde{\Lambda}^{-1} \tilde{D}_{G_\Delta} (d_o + G_\Delta d_i) \ , \end{aligned}$$

can be written as an *error signal* based on y(t) and $y_c(t)$:

$$\begin{aligned} \varepsilon(t,\theta,\psi) &:= (D_c(t) - N_x(t)\Delta_C(t,\theta)) * \eta(t,\psi) \\ \eta(t,\psi) &= \Lambda_o^{-1}(t) * (\tilde{D}_x(t) * y(t) - \tilde{N}_x(t) * y_c(t,\psi)) \end{aligned}$$

# REACT – stability robustness

To guarantee stability of the feedback system during adaptation, we have the following main result:

With

$$\Xi = \{\Delta : \|\Delta\|_\infty < 1/\gamma,\ \Delta \in \mathscr{RH}_\infty\}$$

$$\Pi = \{P : P = (N_x + D_c\Delta_G)(D_x - N_c\Delta_G)^{-1}, \Delta_G \in \Xi\}$$

consider the simultaneously perturbed feedback system in which θ in

$$\Delta_C[u(t)] = \Theta(t)^T \int_0^t (C_D e^{A_D(t-\tau)} B_D + D_D) u(\tau) d\tau$$
$$= \Theta(t)^T (\mathscr{D}(t) * u(t)),$$

is replaced by Ψ. If the time-varying matrix Ψ(t) satisfies

$$\|\Psi(t)\|_2^2 \leq \frac{\gamma^2}{\|\mathscr{D}\|_\infty} \quad \forall t$$

then the feedback system is L2-stable for all $G_\Delta \in \Pi$

# REACT – stability robustness

How can we use this during optimization to guarantee stability robustness?

**Theorem** *Suppose that* $\|\Delta_G\|_\infty < 1/\gamma$, *and the frozen time system* $\Delta_C$ *satisfies* $\|\Delta_C(\Psi)\|_\infty \leq \gamma(1-\delta)$ *for each* $t \geq 0$ *and for some* $0 < \delta < 1$, *and that* $\sup_{t\geq 0}\|\Psi(t)\| < \infty$. *Then there exits an* $\varepsilon > 0$ *such that the feedback system of* $G_\Delta$ *and* $C_\Delta$ *is stable if* $\sup_{t\geq 0}\|\dot{\Psi}(t)\| \leq \varepsilon$.

- Restrict "size" of controller perturbation due to model uncertainty, and
- Restrict "change" in controller parameter update:

$$\dot{\theta} = \mu r(t,\psi) - \mu\Phi(t,\psi)\Phi(t,\psi)^T\theta$$

$$\dot{\psi} = \underset{\psi\in\mathscr{S}}{\mathrm{Proj}}\left(-\lambda\frac{\psi-\theta}{1+\|\psi-\theta\|}\right), \quad \mathscr{S} = \left\{\psi : \|\Psi\|_2 \leq \gamma/\sqrt{\|D\|_\infty}\right\}$$

# REACT – example

*G(q)* discrete-time ZOH equivalent of:

$$G(s)=\frac{K\omega_1^2\omega_2^2}{(s^2+2\beta_1\omega_1 s+\omega_1^2)(s^2+2\beta_2\omega_2 s+\omega_2^2)}$$

controlled by simple PD controller:

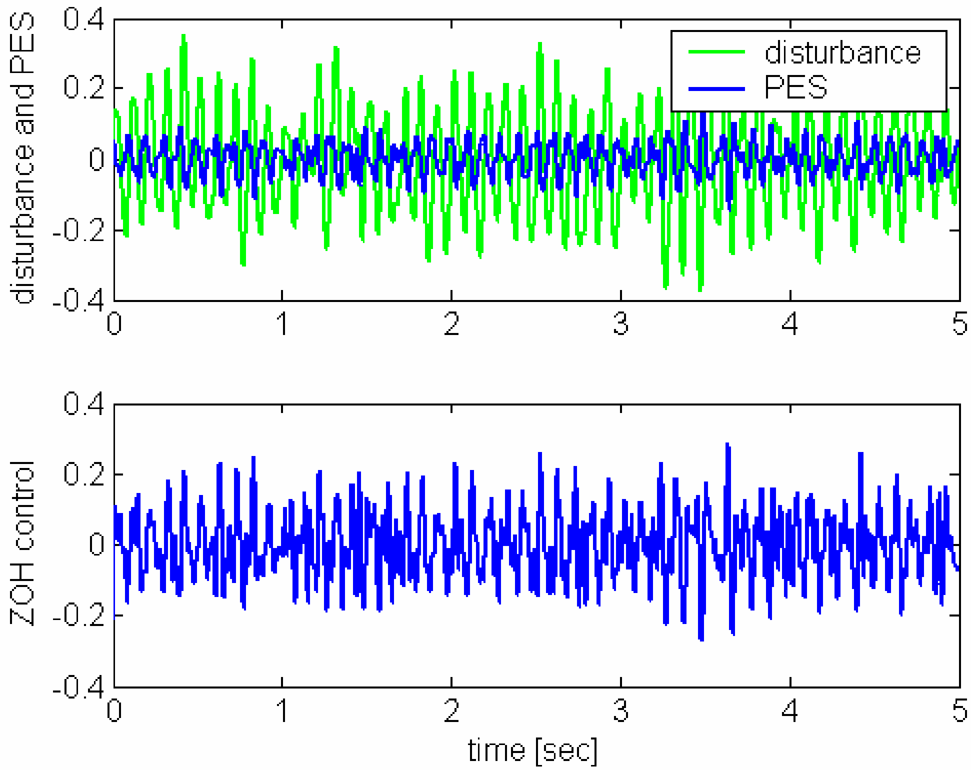
$$C(q)=10\cdot\frac{q-0.995}{q-0.95}$$

Now subjected to disturbance:

$$d(t)=L(q)\varepsilon(t)+0.1\sin(2\pi\cdot 10t)$$

where *L(q)* is a *low pass* filter and *e(t)* is white noise.

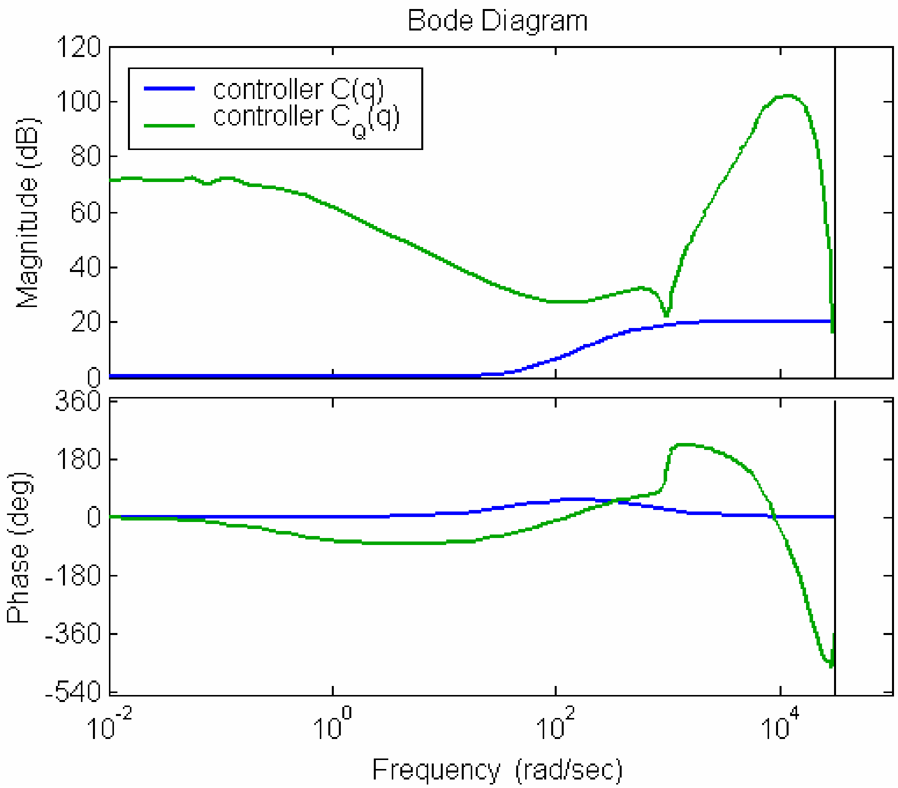
Resulting signals with *C(q)*:



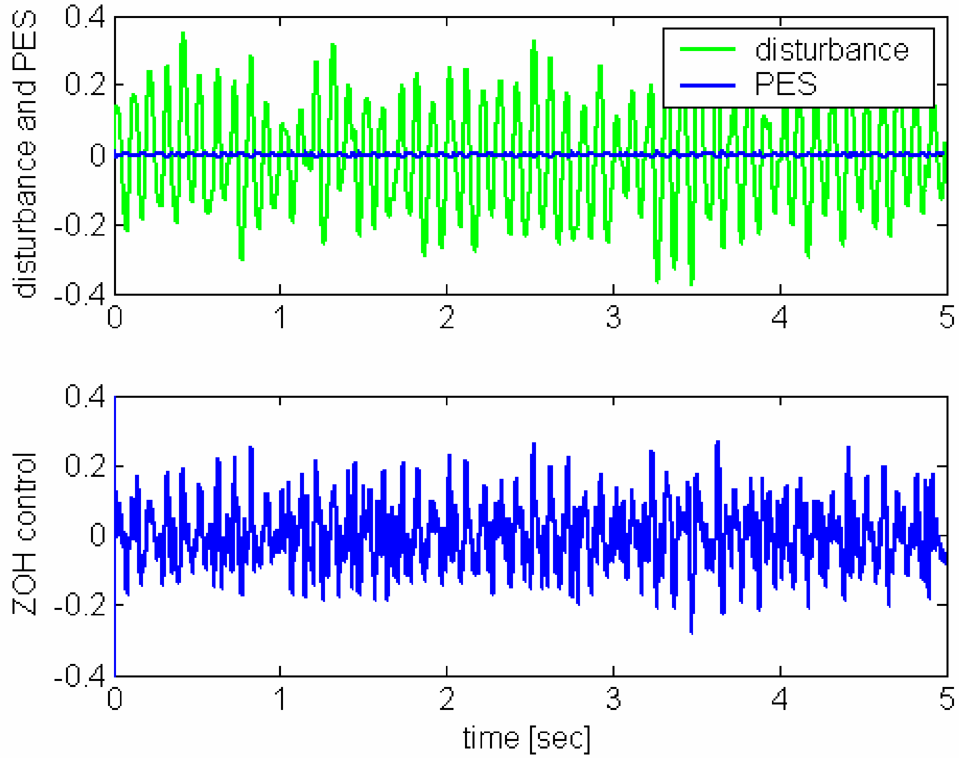
# REACT – example

Running REACT to adapt controller with $\Delta_C(q)$ = 10th order FIR

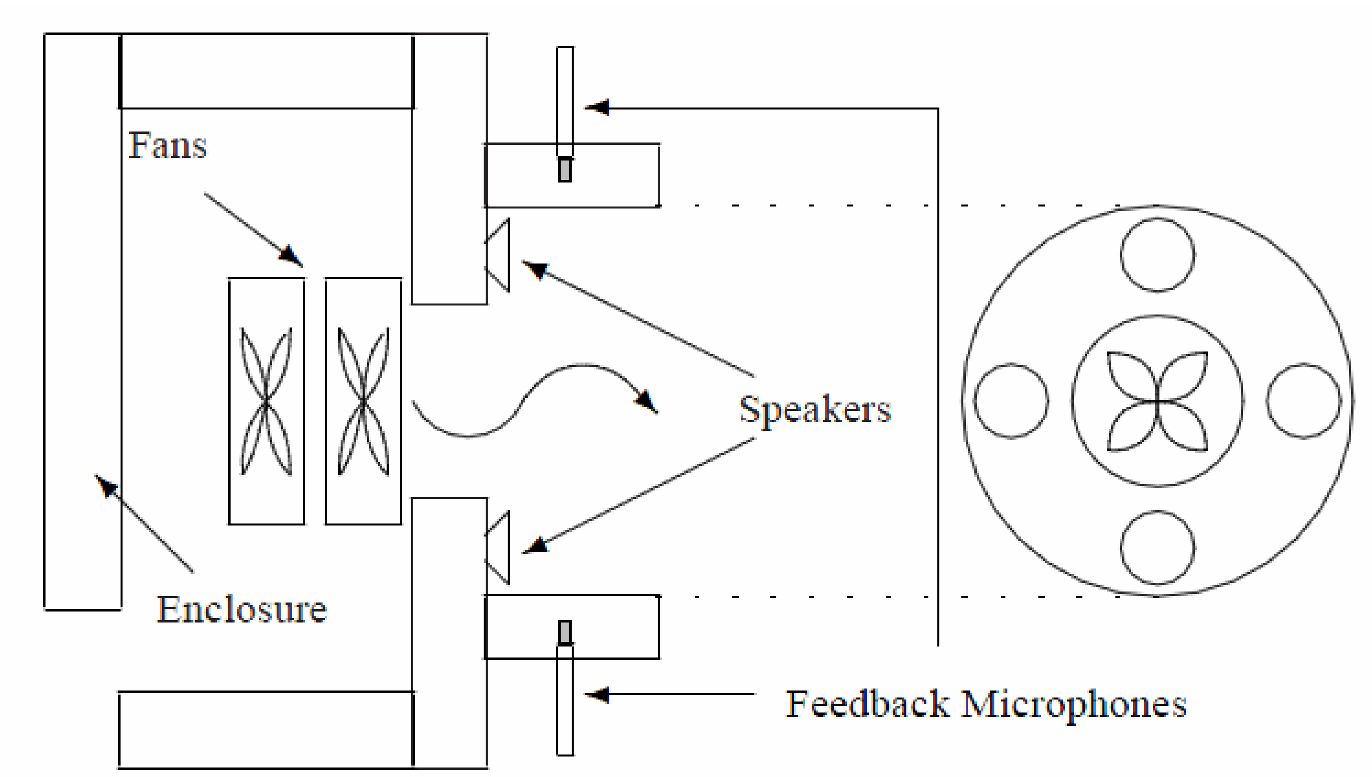
## Adaptation of controller:



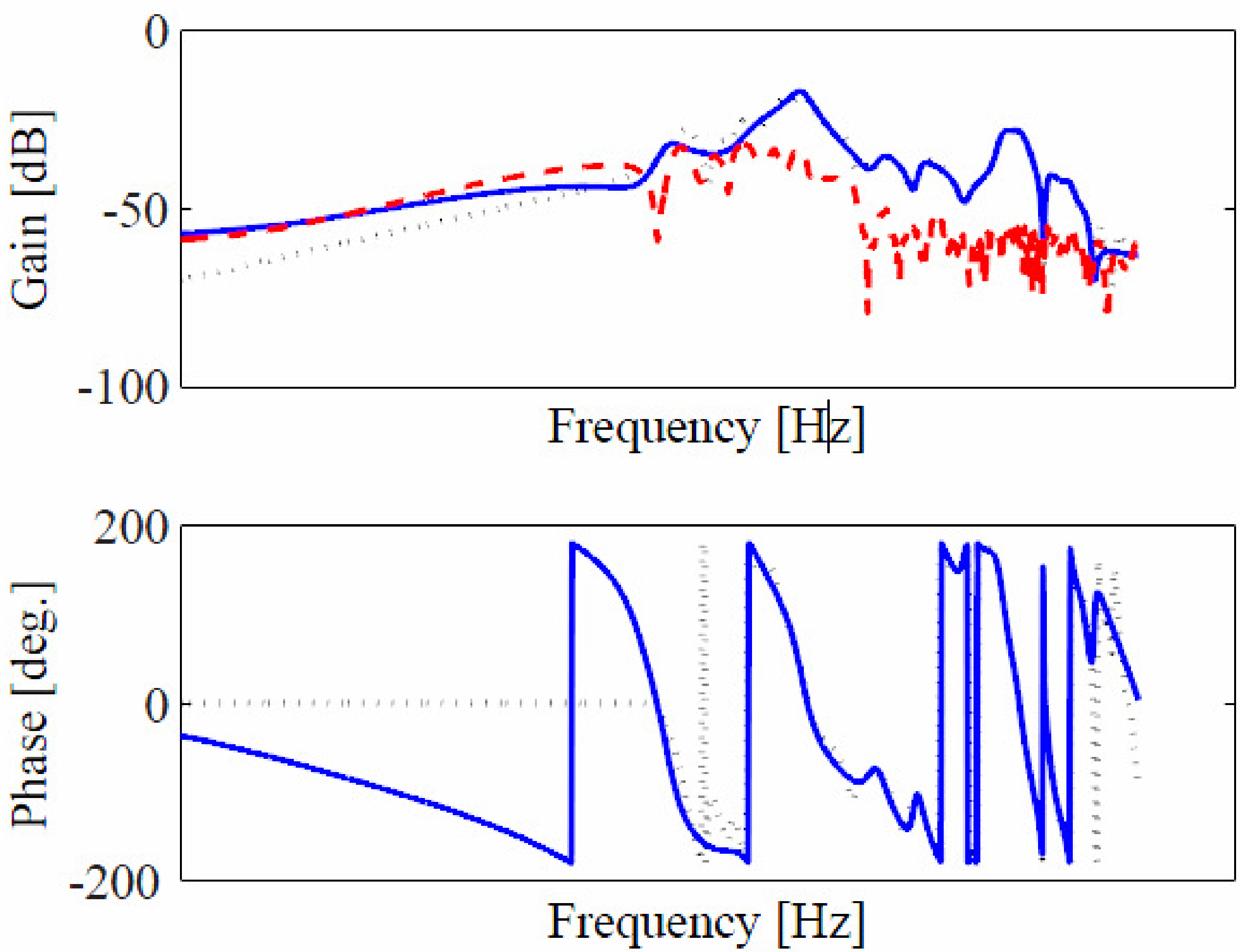

## Resulting signals with $C_\Delta(q)$:



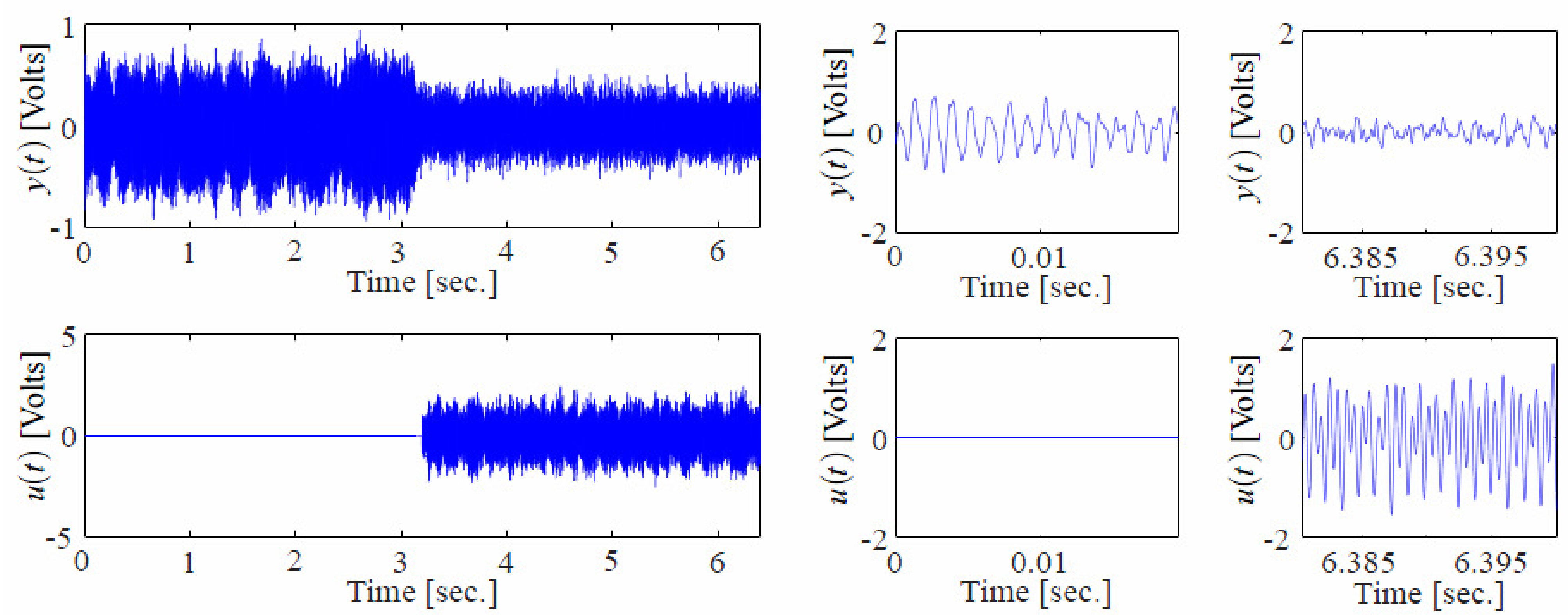
# REACT – application to ANC



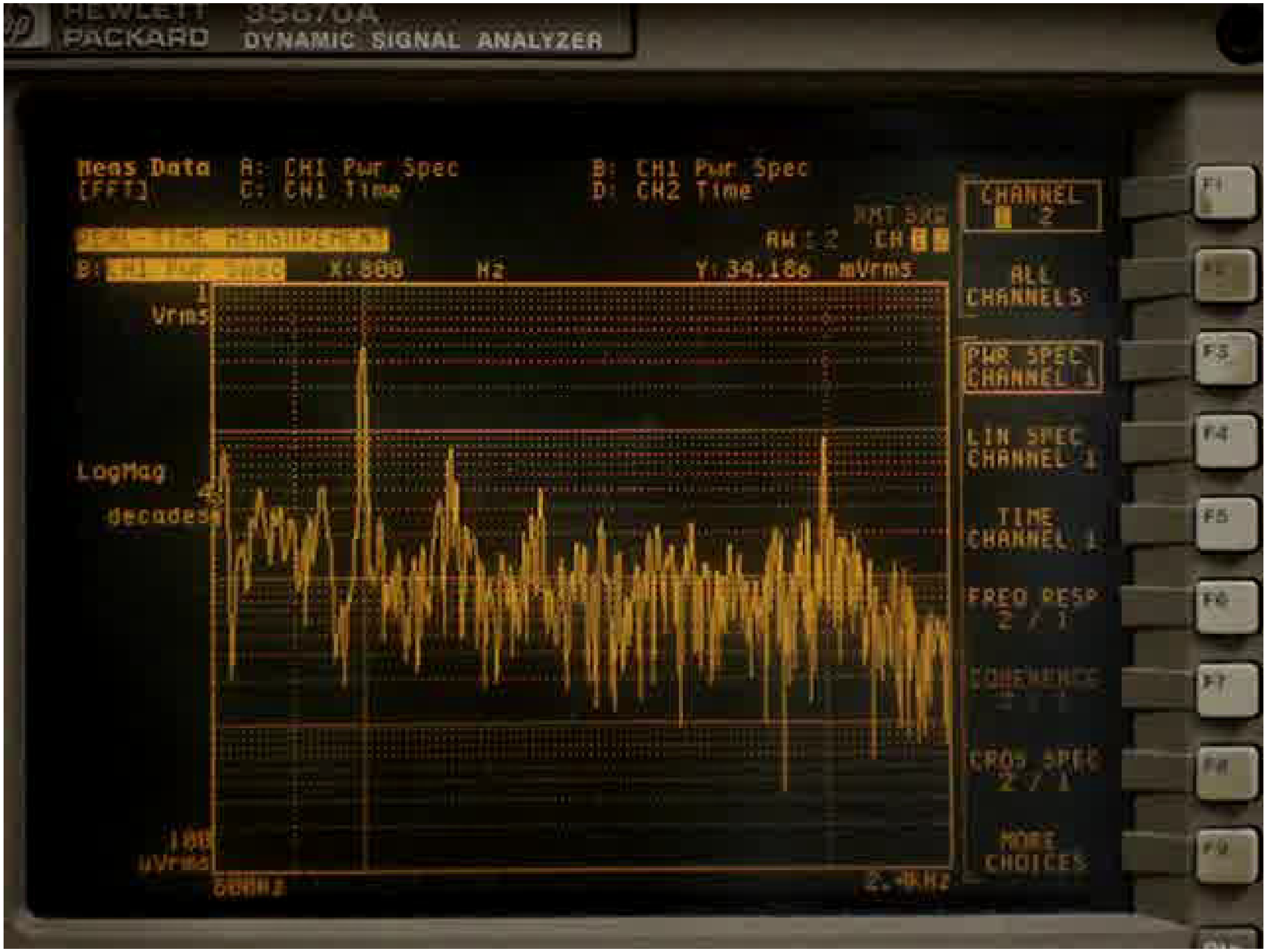

# REACT – application to ANC



# REACT – application to ANC



# REACT – application to ANC



# Wrap up of Technical Part

- Some Hard Facts:
  - Double-Youla parameterization can be used to recast the robust tuning of a feedback controller as a robust estimation problem
  - Robust estimation is obtained by constraining size and change in the parameter estimates so that feedback stability will be maintained during controller tuning in the presence of plant uncertainty
- Some Fun Facts:
  - Applied to ANC system and TAPE servo system by *Charles Kinney*
  - Adjust *existing* feedback based on the disturbances observed
  - Model uncertainty *limits* achievable tuning performance

# Back to the 'hardness on the table'

- Desire to see/share the same enthusiasm and devotion:
  - Control background: combine abstraction with motivating applications
  - Care about students & listen to what they say (TUDelta.27)
  - On vacation/trip: copy a whole bunch off papers
  - Challenge bureaucracy! Perhaps because we like to be in control?
- But make it fun at the same time:
  - Sense of humor and colorful people in a group
  - Spend some time in the lab
  - Get that bottle of wine from the other table
- Proof of devotion:
  - DISC, Leermeesterprijs in 2007 and > 450 students and > 60 PhD
  - Still, visit your PhD student in San Diego and make sure he finishes!
  - Challenge retirement! And enjoy your presence in controls…