Using State-of-the-art NLP Solvers in System Identification and Beyond

Hans D Mittelmann

Department of Mathematics and Statistics
Arizona State University

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Outline

Outline

1. Our Interdisciplinary Research and our Services
   - Our Services (unsupported)
   - Our Interdisciplinary Research (supported)
2. The System Identification Project
   - How it Started; Current status
3. Solving the SYSID Problems
   - The Problems
   - The Solvers
   - An AMPL Script
   - Results
4. Solving other NLP Problems
   - The Categories
   - Typical Results

Everything about Optimization Software

Find, compare, try, download

- Decision Tree for Optimization Software
- Benchmarks for Optimization Software
- Our NEOS Solvers
- Our Testproblems&Software

Decision Tree for Optimization Software

Where to find Links to Software?

- A Guide to (mostly) free Optimization Software
- More than 600 links to software, benchmarks, tools, literature etc

Decision Tree for Optimization Software

The entry Page

Decision Tree for Optimization Software http://plato.asu.edu/guide1.html

Problems/ Software **Benchmarks Testcases** **Books/ Tutorials** **Tools** **Websub- mission** **Other Sources**

Decision Tree for Optimization Software

Search the Decision Tree
Web statistics for server Plato

Welcome! This site aims at helping you identify ready to use solutions for your optimization problem, or at least to find some way to build such a solution using work done by others. If you know of useful sources not listed here, please let us know. If something is found to be erroneous, please let us know, too. Where possible, public domain software is listed here.

Benchmarks for Optimization Software

Current Benchmarks

- COMBINATORIAL OPTIMIZATION
  - Concorde-TSP with different LP solvers (7-8-2005)
- LINEAR PROGRAMMING
  - Benchmark of commercial LP solvers (7-23-2005)
  - Benchmark of free LP solvers (7-23-2005)
- SEMIDEFINITE/SQL PROGRAMMING
  - Several SDP codes on problems from SDPLIB (10-11-2005)
  - Newer SDP/SOCP-codes on the 7th DIMACS Challenge problems(10-11-2005)
  - Several SDP codes on sparse and other SDP problems (9-26-2005)
  - SOCP (second-order cone programming) Benchmark (6-23-2005)

Our Benchmarks

Current Benchmarks (cont.)

- NONLINEAR PROGRAMMING
  - AMPL-NLP Benchmark, IPOPT, KNITRO, LOQO, PENNLP & SNOPT (10-17-2005)
- MIXED INTEGER LINEAR PROGRAMMING
  - MILP Benchmark - free codes (9-26-2005)
- MIXED INTEGER NONLINEAR PROGRAMMING
  - MIQP Benchmark (4-11-2005)
- PROBLEMS WITH EQUILIBRIUM CONSTRAINTS
  - MPEC Benchmark (6-15-2005)

Our NEOS Solvers

Another Free Service to the Community

- Combinatorial Optimization
  - concorde [TSP Input] (only one in category)
- Linear Programming
  - bpmpd [AMPL Input][CPLEX Input][LP Input][MPS Input]
- Mixed Integer Linear Programming
  - feaspump [AMPL Input][CPLEX Input][LP Input][MPS Input]
    scip [AMPL Input][CPLEX Input][LP Input][MPS Input]
- Nondifferentiable Optimization
  - condor [AMPL Input] (only one in category)
- Semi-infinite Optimization
  - nsips [AMPL Input] (only one in category)

Our NEOS Solvers
continued

- Semidefinite Programming (all but one in category)
  - csdp [MATLAB BINARY Input][SPARSE SDPA Input]
  - penbmi [MATLAB Input][MATLAB BINARY Input]
  - pensdp [MATLAB BINARY Input][SPARSE SDPA Input]
  - sdpa [MATLAB BINARY Input][SPARSE SDPA Input]
  - sdpa-c [MATLAB BINARY Input][SPARSE SDPA Input]
  - sdplr [MATLAB BINARY Input][SDPLR Input][SPARSE SDPA Input]
  - sdpt3 [MATLAB BINARY Input][SPARSE SDPA Input]
  - sedumi [MATLAB BINARY Input][SPARSE SDPA Input]

Our Testproblems&Software

Overview of Testproblems

Hundreds of files for various problems and in various formats
Just mention three here:

- Our AMPL collection: 18 directories (LP, QP, MILP, MIQP, NLP; many from own research)
- Our SDP collection: About 60 cases in 2 formats. Is being used by authors to improve their codes
- Our MILP collection: many from NEOS submissions

Our Software Collection

Minor

- Binaries of some free/non-free software
- Sources of DONLP2 and other codes by Peter Spellucci
- Sources of codes not available elsewhere (authors "disappeared" etc)

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Applications of Optimization
In the Real World

- Supply Chain Management (Intel Corp), NSF-0432439
  - Mainly LP/QP until now; SOCP, NLP in the future
  - Mostly Matlab; MPC, discrete event simulation (DEVSJAVA)
- System Identification (process industries), ACS-3760-AC9
  - Challenging NLPs
  - AMPL models, NLP solvers with AMPL interface

Outline

An Interdisciplinary Project

thanks to my college

- In Spring 2001 my college (Liberal Arts & Sciences) granted me an internal Sabbatical for interdisciplinary research
- Total of 10 papers so far; see http://plato.asu.edu/papers/
- Collaborated with Daniel Rivera (Chem. Mat. Eng.) on the following project (for simplicity slides of joint talk)

Optimization-based design of multisine signals for “plant-friendly” identification of highly interactive systems

Hans D. Mittelmann*, Gautam Pendse

Department of Mathematics and Statistics

College of Liberal Arts and Sciences

Arizona State University, Tempe, AZ 85287

Hyunjin Lee, Daniel E. Rivera

Control Systems Engineering Laboratory

Department of Chemical and Materials Engineering

Ira A. Fulton School of Engineering

*mittelmann@asu.edu (480)-965-6595

Presentation Outline

- **Multivariable System Identification using Multisine Signals**
  - Extension to highly interactive systems using modified “zippered” spectra
  - Optimization-based formulations for minimum crest factor signals, conducive to “plant-friendliness”

- **Case Study: High-Purity Distillation Column (Weischedel-McAvoy)**
  - Optimization-based design using an *a priori* ARX model
  - Closed-loop evaluation of data effectiveness with MPC
  - Extension to input signal design for nonlinear identification using NARX models

- **Latest Efforts:**
  - Input signal design for data-centric estimation (such as MoD)

System Identification Challenges Associated with Highly Interactive Processes:

- Need to capture both low and high gain directions under noisy conditions
- Plant-friendliness must be achieved during identification testing

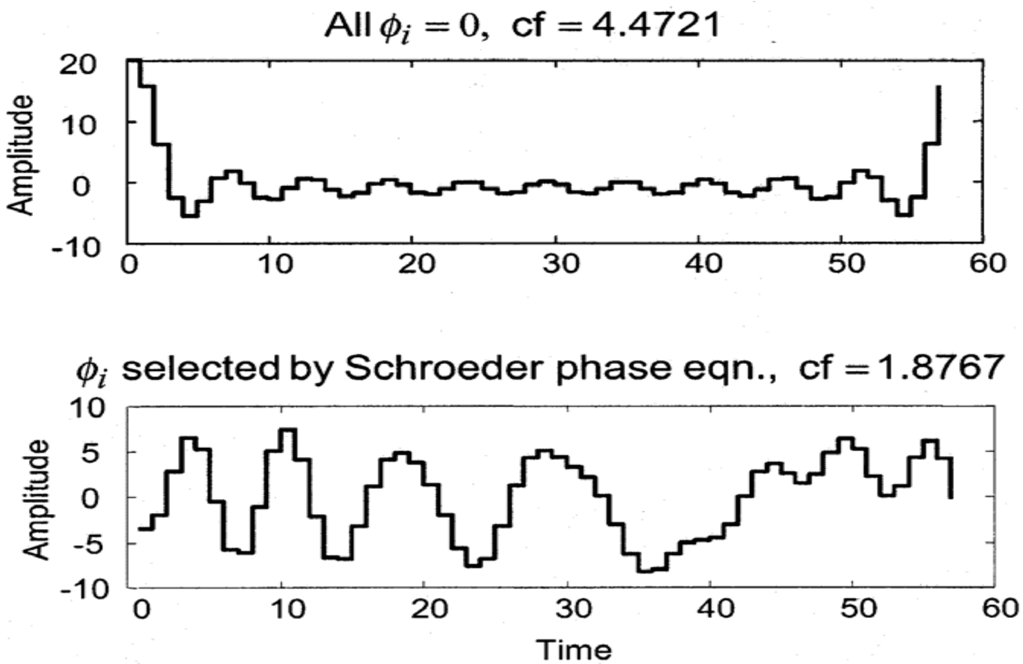
Plant-Friendly Identification Testing

- A plant-friendly input signal should:
  - be as short as possible
  - not take actuators to limits, or exceed move size restrictions
  - cause minimum disruption to the controlled variables (i.e., low variance, small deviations from setpoints)

The Crest Factor (CF) is defined as the ratio of ℓ_∞ (or Chebyshev) norm and the ℓ_2 norm

$$\boxed{CF(x) = \frac{\ell_\infty(x)}{\ell_2(x)}}$$

A low crest factor indicates that most elements in the input sequence are located near the min. and max. values of the sequence.



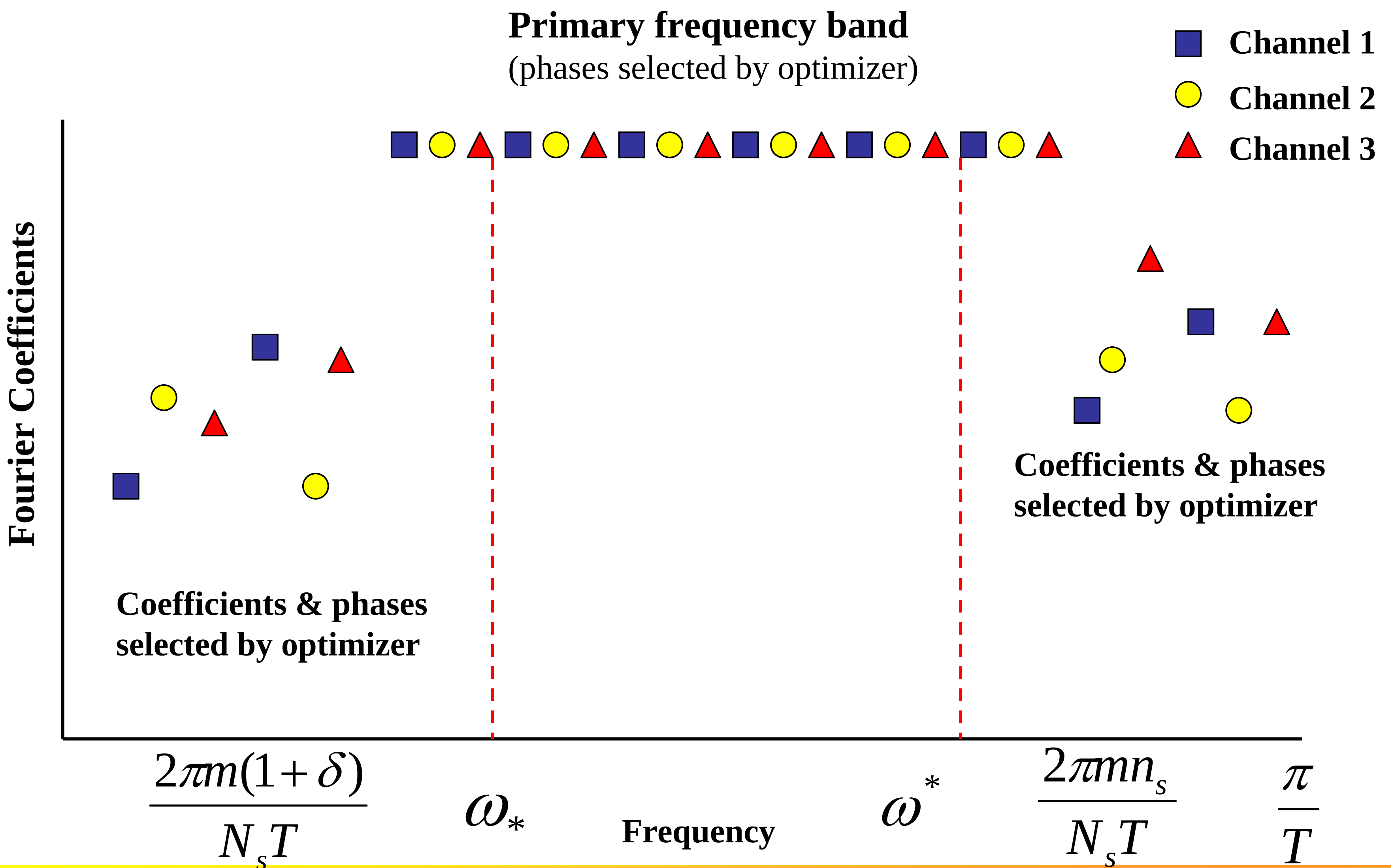
Multisine Input Signals

A multisine input is a deterministic, periodic signal composed of a harmonically related sum of sinusoids,

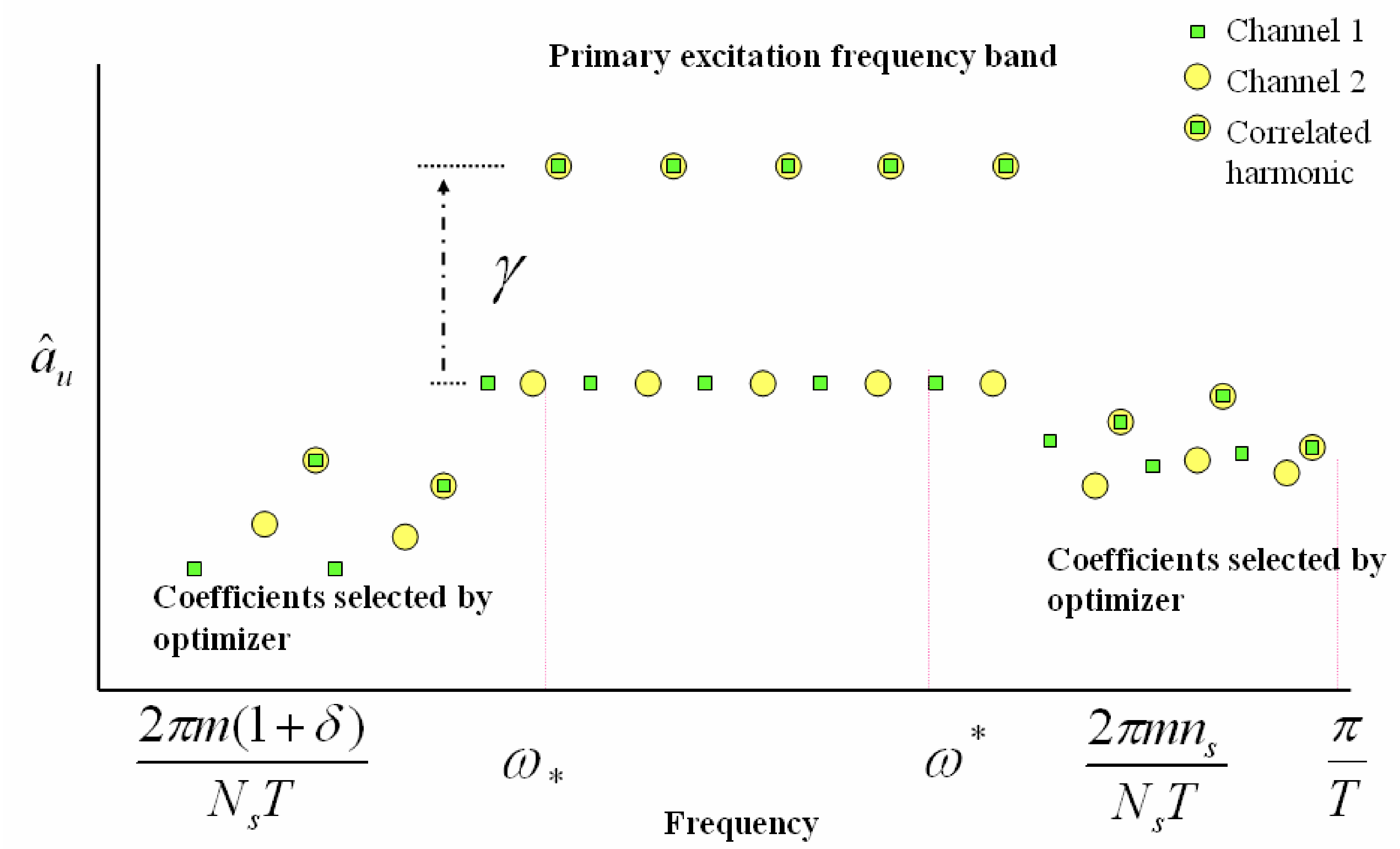
$$
\begin{aligned}
u_j(k) \quad = \quad & \sum_{i=1}^{m\delta} \hat{\delta}_{ji} \cos(\omega_i kT + \phi_{ji}^{\delta}) + \sum_{i=m\delta+1}^{m(\delta+n_s)} \alpha_{ji} \cos(\omega_i kT + \phi_{ji}) \\
& + \sum_{i=m(\delta+n_s)+1}^{m(\delta+n_s+n_a)} \hat{a}_{ji} \cos(\omega_i kT + \phi_{ji}^{a}), \quad j = 1, \cdots, m
\end{aligned}
$$

where T is sampling time, N_s is the sequence length, m is the number of channels, δ, n_s, n_a are the numbers of sinusoids per channel ($m(\delta+n_s+n_a) = N_s/2$), $\phi_{ji}^{\delta}, \phi_{ji}, \phi_{ji}^{a}$ are the phase angles, α_{ji} represents the Fourier coefficients defined by the user, $\hat{\delta}_{ji}, \hat{a}_{ji}$ are the "snow effect" Fourier coefficients

Standard Zippered Spectrum



Modified Zippered Spectrum



Problem Statement #1

$$\min_{\{\phi^a_{ji}\},\{\phi^\delta_{ji}\},\{\phi_{ji}\},\{\hat{a}_{ji}\},\{\hat{\delta}_{ji}\}} \max_j \ \mathsf{CF}(u_j) \quad j = 1, \cdots, m$$

subject to maximum move size constraints on $\{u_j(k)\}$

$$|\Delta u_j(k)| \leq \Delta u_j^{max} \quad \forall\, k, j$$

and high/low limits on $\{u_j(k)\}$

$$u_j^{min} \leq u_j(k) \leq u_j^{max} \quad \forall\, k, j$$

Problem Statement #2

$$\min_{\{\phi^a_{ji}\},\{\phi^b_{ji}\},\{\phi_{ji}\},\{\hat{a}_{ji}\},\{\hat{b}_{ji}\}} \max_{z} \mathsf{CF}(y_z)$$

$$j = 1, \cdots, m \qquad z = 1, \cdots, N_{outs}$$

subject to constraints in input

$$|\Delta u_j(k)| \leq \Delta u_j^{max} \quad \forall\, k, j$$

$$u_j^{min} \leq u_j(k) \leq u_j^{max} \quad \forall\, k, j$$

and output

$$|\Delta y_z(k)| \leq \Delta y_z^{max} \quad \forall\, k, z$$

$$y_z^{min} \leq y_z(k) \leq y_z^{max} \quad \forall\, k, z$$

This problem statement requires an *a priori* model to generate output predictions

Case Study: High-Purity Distillation

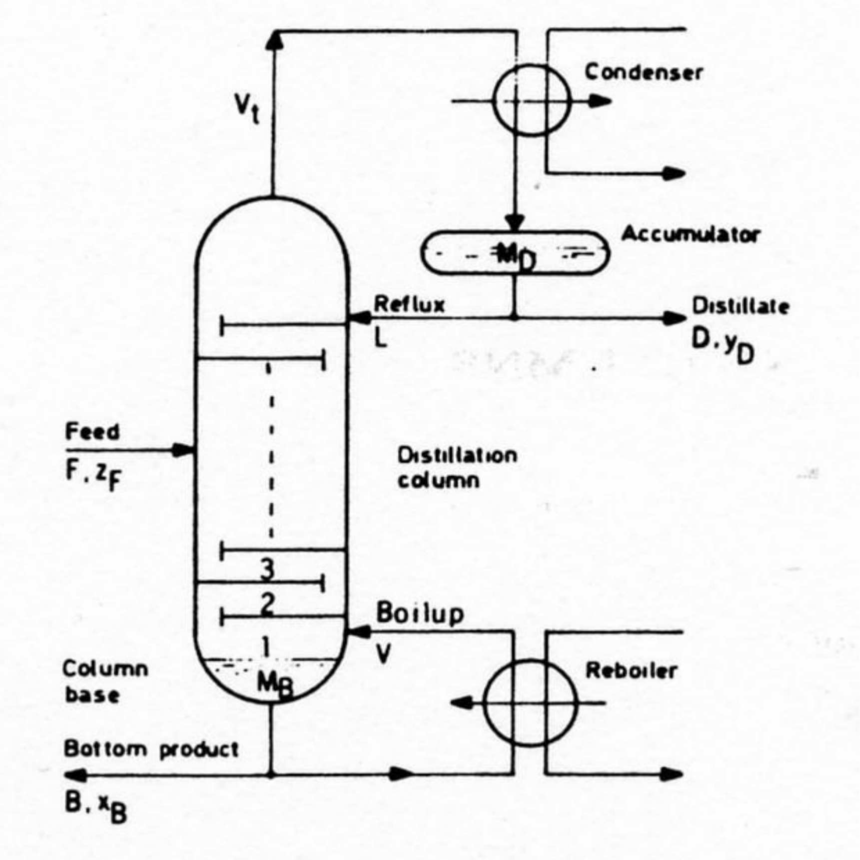
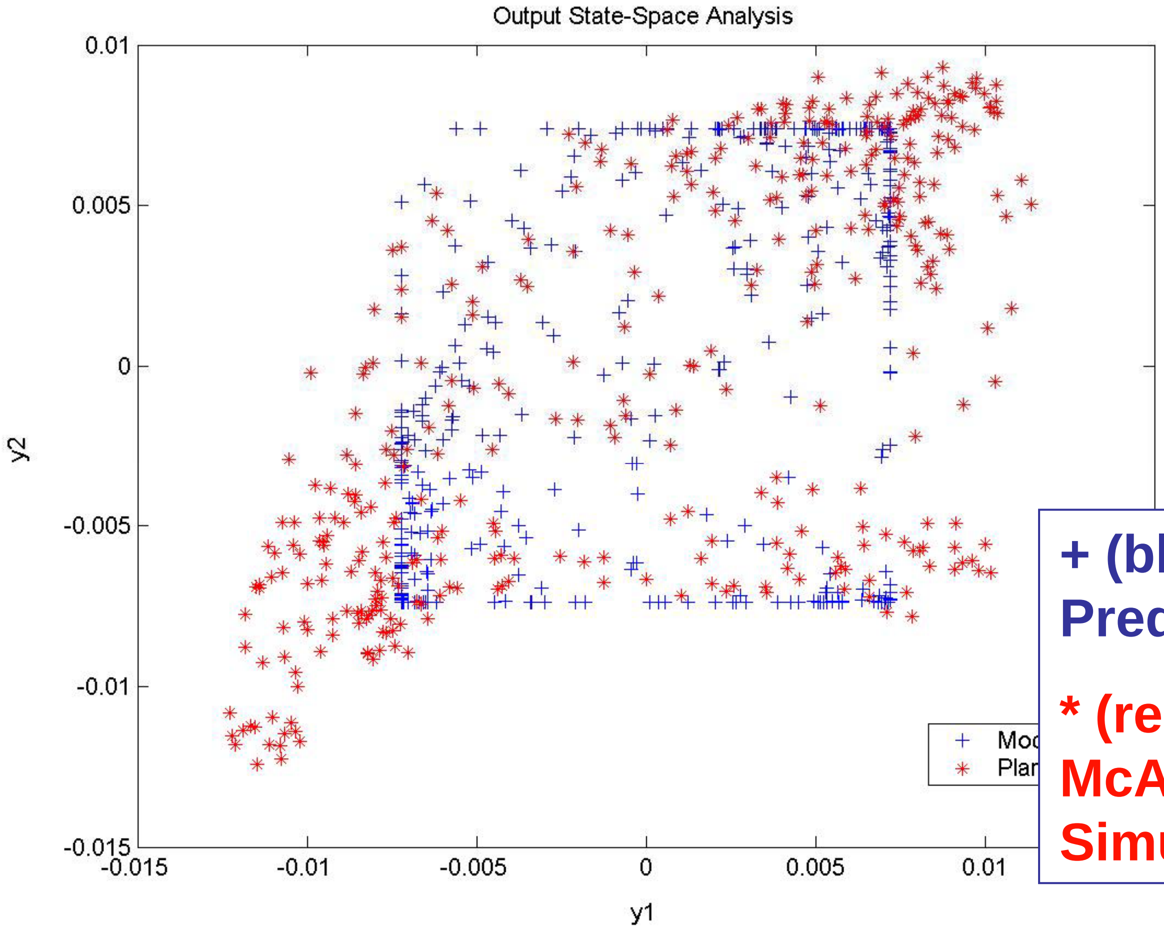


Fig. 2. Two-product distillation column.

High-Purity Distillation Column per Weischedel and McAvoy (1980) : a classical example of a highly interactive process system, and a challenging problem for control system design

ARX Model Prediction vs. Plant Data



+ (blue) : Model Prediction

*** (red) : Weischedel-McAvoy Distillation Simulation**

NARX Model Estimation

Rely on a NARX model equation to predict the system outputs during optimization:

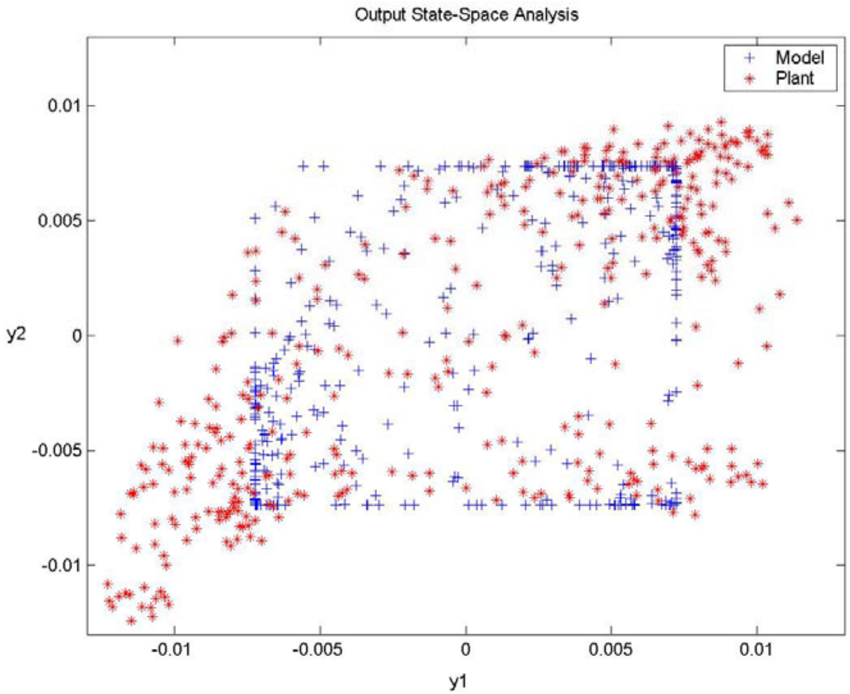
$$y(k) = \theta^{(0)} + \sum_{i=1}^{n_y} \theta_i^{(1)} y(k-i) + \sum_{i=\rho}^{n_u} \theta_i^{(2)} u(k-i) + \sum_{i=1}^{n_y} \sum_{j=1}^{i} \theta_{(i,j)}^{(3)} y(k-i) y(k-j)$$
$$+ \sum_{i=\rho}^{n_u} \sum_{j=\rho}^{i} \theta_{(i,j)}^{(4)} u(k-i) u(k-j) + \sum_{i=1}^{n_y} \sum_{j=\rho}^{n_u} \theta_{(i,j)}^{(5)} y(k-i) u(k-j) + \ldots$$

Evaluation criterion (Sriniwas *et al.*, 1995):

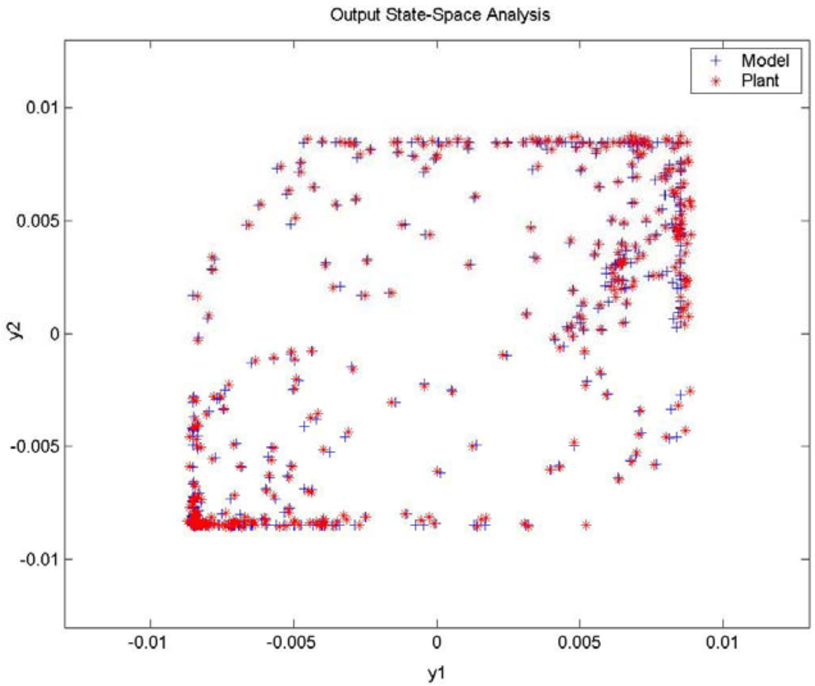
$$I = \frac{\sum_{k=1}^{N} [y(k) - \hat{y}(k)]^2}{\sum_{k=1}^{N} [y(k) - \bar{y}(k)]^2} \times 100\%$$

ARX vs. NARX Model Predictions

ARX Model



NARX Model



+ (blue) : Model Prediction

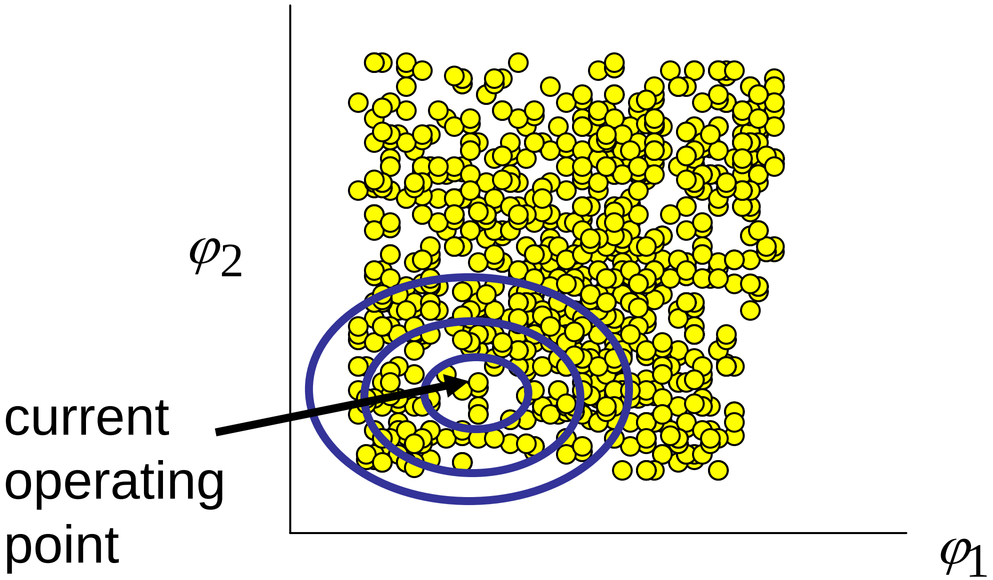
*** (red) : Weischedel-McAvoy Distillation Simulation**

Model-on-Demand Estimation

(Stenman, 1999)

- A modern data-centric approach developed at Linkoping University

- Identification signals geared for MoD estimation should consider the geometrical distribution of data over the state-space.



Weyl Criterion

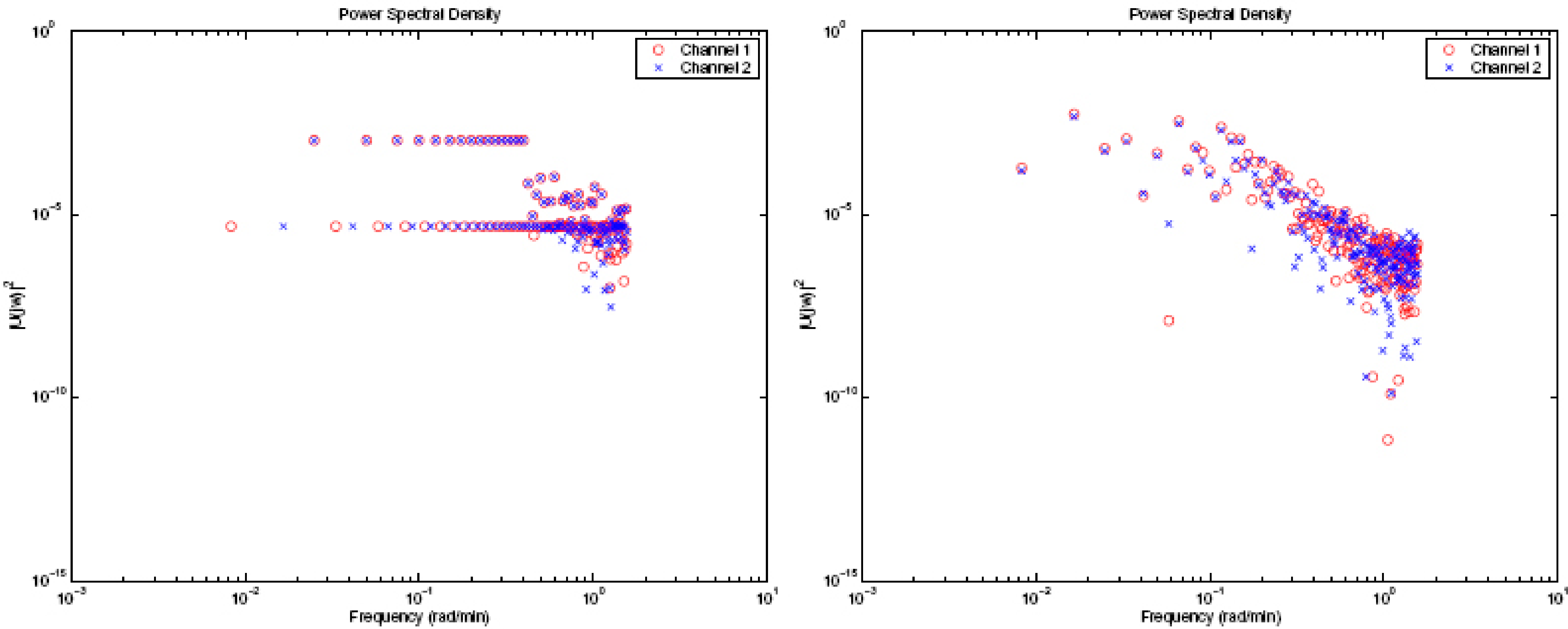
Theorem (H. Weyl, 1916) *A sequence* $\{y_n^1, y_n^2\}$ *is equidistributed in* $[0,1)^2$ *if and only if*

$$\lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} e^{2\pi i(l_1 y_n^1 + l_2 y_n^2)} = 0$$

$\forall$ *sets of integers* l_1, l_2 *not both zero.*

$$\lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} \cos[2\pi(l_1 y_n^1 + l_2 y_n^2)] = 0$$

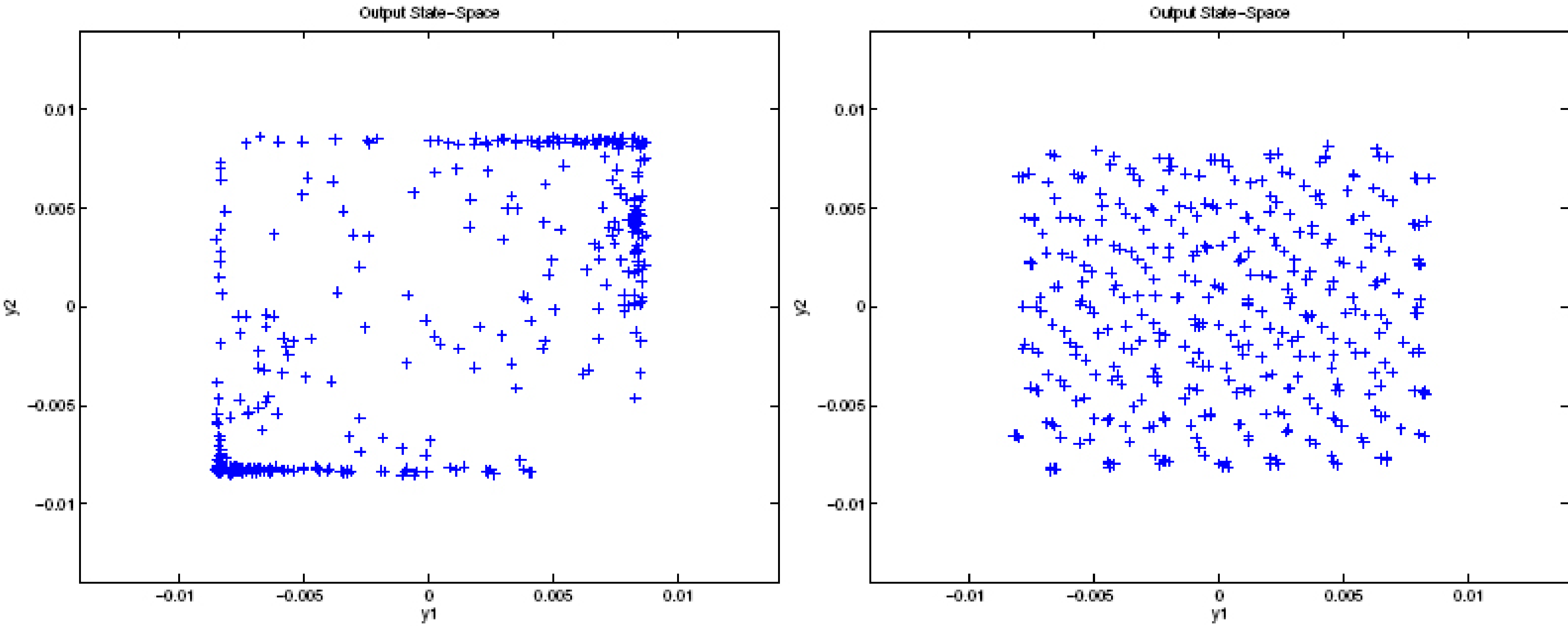
$$\lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} \sin[2\pi(l_1 y_n^1 + l_2 y_n^2)] = 0$$



a. min CF (y)

b. Weyl-based Approach

Figure 5. Input power spectral densities for Weischedel-McAvoy distillation column: min CF(y) modified zippered spectrum signal (a) versus Weyl-based design (b)



a. min CF (y) b. Weyl-based Approach

Figure 6. Output state-space analysis for Weischedel-McAvoy distillation column: min CF(y) modified zippered spectrum signal (a) versus Weyl-based design (b)

Outline

Five typical Problems

from small/easy to large/difficult

- Weyl-m0:
  Model 0 from Skogestad&Morari (1988), see paper 100
- WM-CFx, WM-CFy:
  Two Weischedel-McAvoy cases, crestfactor minimization, see paper 103
- NARX-CFy, NARX-Weyl:
  Two nonlinear NARX cases, see papers 103, 106

Outline

Commercial and Free Codes

state-of-the-art

- IPOPT-3.0.0
  http://projects.coin-or.org/Ipopt
- KNITRO-4.0
  http://www.ziena.com/knitro.html (it/dir)
- LOQO-6.06
  http://www.princeton.edu/ rvdb/
- PENNLP-2.2b
  http://www.penopt.de/pennlp.html
- SNOPT-7.2-1
  http://www.scicomp.ucsd.edu/ peg/

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```
param N integer := 210;
param Nu integer :=  105;
param a1{1..Nu};
param a2{1..Nu};
var a1v{i in 1..Nu} := a1[i];
var a2v{i in 1..Nu} := a2[i];
param mx := .5;
param k{i in 1..N} := i;
param pi := 4*atan(1);
param alp :=exp(-15/75);
param kk{1..2,1..2};
param pn{i in 1..Nu} := i*2*pi/N;
var alpha{1..Nu,1..2};
var x{i in 0..N-1,j in 1..2} := .1;
var y{i in 0..2*N-1, j in 1..2} := .1;
```

```
param bdy := .5;
param t := 1e-2;
param lim := 6; # Weyl Theorem in (-6,6)
set S1 := -lim..0;
set S2 := 1..lim;
set S := S1 union S2;
set W := {i in S,j in S:not(i==0 and j==0)};

s.t. weyl1{(m1,m2) in W}: sum{n in N..2*N-1}
cos(2*pi*(m1*(y[n,1]+0.5)+m2*(y[n,2]+0.5)))<=t;
     weyl2{(m1,m2) in W}: sum{n in N..2*N-1}
sin(2*pi*(m1*(y[n,1]+0.5)+m2*(y[n,2]+0.5)))<=t;

 fix{i in 1..9}: a1v[3*i]=a2v[3*i];
bound{j in N..2*N-1,i in 1..2}: -bdy<=y[j,i]<=bdy;
```

```
s.t. inp{i in 0..N-1, j in 1..2}:
  x[i,j]= if j==1 then sum{u in 1..Nu}
    (a1v[u]*cos(pn[u]*k[i+1]+alpha[u,j]))
  else sum{u in 1..Nu}
    (a2v[u]*cos(pn[u]*k[i+1]+alpha[u,j]));

  out1{i in 1..N,j in 1..2}: y[i,j]=alp*
y[i-1,j]+(1-alp)*sum{l in 1..2}kk[j,l]*x[i-1,l];
  out2{i in N+1..2*N-1,j in 1..2}: y[i,j]=alp*
y[i-1,j]+(1-alp)*sum{l in 1..2}kk[j,l]*x[i-N-1,l];
move1{i in 0..N-2,j in 1..2}:
   -mx<=x[i+1,j]-x[i,j]<=mx;
move2{j in 1..2}: -mx<=x[0,j]-x[N-1,j]<=mx;
```

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The platform

- P4, 3.2 GHz, 3.7 GB
- Linux
- for the benchmark results below
    - 2-hour time limit

problem	variables	constraints
WM_CFx	8520	9826
WM_CFy	8520	9826
Weyl_m0	1680	2049
NARX_CFy	43973	46744
NARX_Weyl	44244	45568

IPOPT	KNITRO	-D	LOQO	PENNLP	SNOPT
997	2941	3427	2171	fail	8821
16318	3706	2052	2277	fail	3180
>21000	774	2042	fail	3516	>66000
90977	6033!	>150000	fail	fail	fail
fail	25743!		fail	fail	fail

Outline

www-unix.mcs.anl.gov/~more/cops/
www.sor.princeton.edu/~rvdb/ampl/nlmodels/cute/
plato.asu.edu/pub/ampl_files/ellip_ampl/
plato.asu.edu/pub/ampl_files/lukvl_ampl/
plato.asu.edu/pub/ampl_files/parabol_ampl/
plato.asu.edu/pub/ampl_files/nlp_ampl/
plato.asu.edu/pub/ampl_files/globallib_ampl/
plato.asu.edu/pub/ampl_files/rqcqp_ampl/
plato.asu.edu/pub/ampl_files/qcqp_ampl/

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problem	variables	constraints
gasoil_3200	32001	31998
henon_120	32401	241
cont5_2_1_l	90600	90300
qssp180	261365	139141
lukvli10	250000	249998

IPOPT	KNITRO	-D	LOQO	PENNLP	SNOPT
27	1165	45	114	166	1007
3624	822	4417	1787	852	t
1781	288	274	t	493	t
502	1619	535	m	338	t
317	94	204	104	328	t

THE END

Thank you for your attention

Questions or Remarks?

PDF of talk at: http://plato.asu.edu/talks/