CR-IDENT: A MATLAB TOOLBOX FOR MULTIVARIABLE CONTROL-RELEVANT SYSTEM IDENTIFICATION

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Abstract: This paper describes CR-IDENT, a Matlab-based toolbox that implements a comprehensive procedure for multivariable control-relevant system identification aimed primarily at process system applications. The toolbox consists of modules for multivariable input signal design (multisine and PRBS), frequency response estimation, and control-relevant frequency response curvefitting, leading to models whose end use is the design of high-performance control systems. An important component in the implementation of this design procedure is its reliance on *a priori* knowledge of the system of interest to design input signals meeting both theoretical and practical user requirements. Data from identification testing using these signals is the basis for the subsequent steps of frequency-response estimation and control-relevant parameter estimation, with the final result being a discrete-time state-space model that serves as the nominal model for Model Predictive Control. A high-purity distillation column example is presented to illustrate the benefits of the toolbox, from experiment design to closed-loop control.

Keywords: multivariable system identification, input signal design, control-relevant modeling

1. INTRODUCTION

Improving the link between system identification and control design has been a subject of great interest in the control systems literature for nearly two decades (Hjalmarsson, 2005). There is a continuing need for control-relevant identification methodologies focused on multivariable problems that appeal to both academic and industrial practitioners. In principle, such methodologies should be comprehensive in nature, take full advantage of *a priori* knowledge of a system to be identified, be as short and non-invasive as possible to the process (i.e., “plant-friendly”), and not make substantial demands on user-skill levels in its implementation (Rivera *et al.*, 2003). Based on recent research activities in the Control Systems Engineering Laboratory at Arizona State University, CR-IDENT is a Matlab-based toolbox that implements a comprehensive procedure for multivariable control-relevant system identification with these goals in mind. The functionality implemented in CR-IDENT is summarized in Figure 1. Although aimed primarily at process system applications, the methodology is broadly-applicable and can be useful in multiple application domains.

The toolbox consists of modules for multi-channel input signal design (multisine and PRBS), frequency-response estimation, and control-relevant frequency-response curvefitting. These modules can be used independently or as part of an integrated procedure as shown in Figure 1. The functionality of each toolbox is accessed with a graphical user interface (GUI) to provide flexibility and convenience to the user. This toolbox is designed using Matlab R14 with Service Pack 3 (Version 7.1) and requires the Signal Processing, Control System, System Identification, and Model Predictive Control Toolboxes as well as Simulink. The theoretical background behind the toolbox is described in various papers by Lee *et al.* (2003*a*; 2003*b*) and Lee and Rivera (2004; 2005*a*; 2005*b*).

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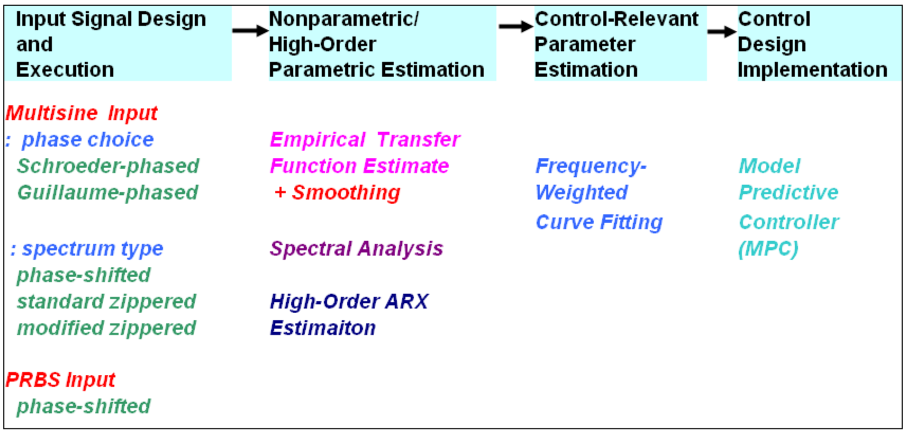

Fig. 1. Summary of the design procedure and functionality available in CR-IDENT, a comprehensive framework for multivariable control-relevant system identification.

This paper presents the general features of the toolbox and describes an illustrative example based on a high-purity distillation column case study. In particular, the design of three types of multisine input designs supported by the toolbox is demonstrated and data arising from these designs is used to obtain models which are evaluated on Model Predictive Control of this system. The paper is organized as follows: Section 2 describes the individual GUIs that comprise the CR-IDENT Toolbox. Section 3 presents the case study, while Section 4 provides a summary and conclusions.

2. CR-IDENT: A MATLAB-BASED TOOLBOX

Invoking the command

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>> crident
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calls a general menu (see Figure 2) with options corresponding to each of the three GUIs that comprise CR-IDENT. Salient aspects for each GUI module are described in this section.


CR-IDENT: Control-Relevant System Identification

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Fig. 2. Main GUI for CR-IDENT, a toolbox for multivariable control-relevant identification.

2.1 *Multivariable Multisine Input Signal Design*

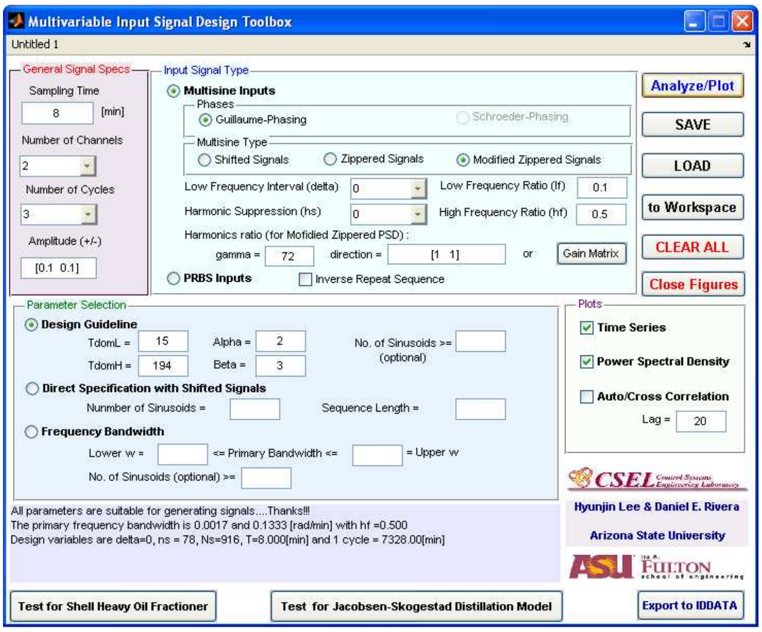
By enabling direct specification of the power spectrum, multisine signals provide a versatile class of inputs for accomplishing system identification (see Figure 3). A multisine input $u_j(k)$ for the j-th channel of a multivariable system with m inputs is defined as,

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

where m is the number of channels, δ, n_s, n_a are the number of sinusoids per channel ($m(\delta + n_s + n_a) = N_s/2$), $\phi^{\delta}_{ji}, \phi_{ji}, \phi^{a}_{ji}$ are the phase angles, and $\hat{\delta}_{ji}$, α_{ji}, & $\hat{a}_{ji}$ represents the Fourier coefficients defined by the user.

The principal design guideline implemented in CR-IDENT uses *a priori* knowledge of dominant time constants of the system and speed of the response specifications to define a primary bandwidth for excitation in the signal (Lee *et al.*, 2003*b*; Lee and Rivera, 2005*b*). This bandwidth is translated into a series of inequalities that determine the number of sinusoids (n_s), sequence length (N_s), and sampling time (T_s). For users not wishing to use these guidelines, the input GUI supports direct parameter specification with a verification routine to insure proper implementation.

The input design GUI (Figure 3) offers various options for multi-channel implementation such as phase-shifted, orthogonal (“zippered”) spectrum, and modified zippered spectrum designs (Lee and Rivera, 2004). The shifted multisine input design adopts a technique well-known in the literature for pseudo-random signals in which multiple channels are shifted relative to each other in order to reduce the interactions between channels. A similar feature is available for PRBS signals. A zippered power spec-


Multivariable Input Signal Design Toolbox

Untitled 1

General Signal Specs
Sampling Time 8 [min]
Number of Channels 2
Number of Cycles 3
Amplitude (+/-) [0.1 0.1]

Input Signal Type
● Multisine Inputs
Phases: ● Guillaume-Phasing ○ Schroeder-Phasing
Multisine Type: ○ Shifted Signals ○ Zippered Signals ● Modified Zippered Signals
Low Frequency Interval (delta) 0
Low Frequency Ratio (lf) 0.1
Harmonic Suppression (hs) 0
High Frequency Ratio (hf) 0.5
Harmonics ratio (for Mofidied Zippered PSD) :
gamma = 72 direction = [1 1] or Gain Matrix
○ PRBS Inputs ☐ Inverse Repeat Sequence

Parameter Selection
● Design Guideline
TdomL = 15 Alpha = 2 No. of Sinusoids >= (optional)
TdomH = 194 Beta = 3
○ Direct Specification with Shifted Signals
Nunmber of Sinusoids = Sequence Length =
○ Frequency Bandwidth
Lower w = <= Primary Bandwidth <= = Upper w
No. of Sinusoids (optional) >=

Plots
☑ Time Series
☑ Power Spectral Density
☐ Auto/Cross Correlation
Lag = 20

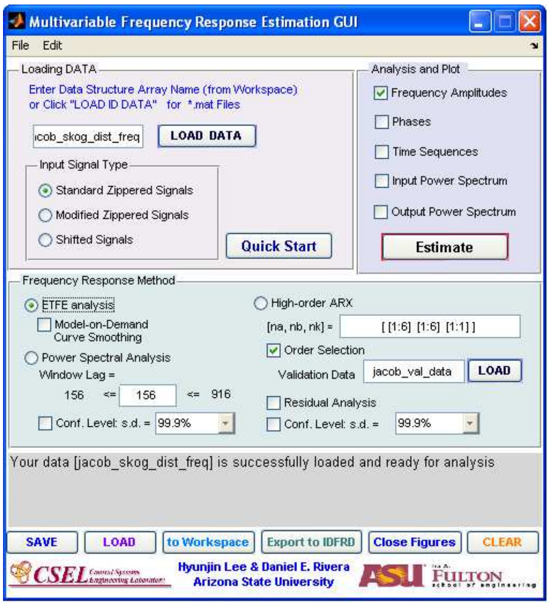
All parameters are suitable for generating signals....Thanks!!!
The primary frequency bandwidth is 0.0017 and 0.1333 [rad/min] with hf =0.500
Design variables are delta=0, ns = 78, Ns=916, T=8.000[min] and 1 cycle = 7328.00[min]

Fig. 3. Multivariable Input Signal Design GUI in CR-IDENT.

trum design gives orthogonality to individual input channels so that only one input channel is excited at each point in the frequency grid. The result of this approach is longer lengths relative to shifted signals, but with lower levels of cross-correlation.

For the case of strongly interactive systems, CR-IDENT offers a multisine signal with modified zippered spectrum option that contains both correlated and uncorrelated harmonics, respectively, over the frequency bandwidth. A modified zippered spectrum is able to offer a directional signal design that can be used to excite specific gain directions in a multivariable system, such as the low-gain direction; this is a critical consideration in the identification of highly-interactive systems (Lee *et al.*, 2003*b*; Lee and Rivera, 2005*b*). If users provide a gain matrix, the GUI computes the system gain directions and adjusts the signal's input directions and power amplitudes to produce a more balanced output state-space distribution (Lee and Rivera, 2005*b*).

For all multisine signal choices shown in Figure 3, the phases can be obtained either through the closed-form formula by Schroeder (1970) or though the iterative *p*-norm optimization approach that minimizes crest factor developed by Guillaume *et al.* (1991). Signals can be validated in both time and frequency domains, and exported in either "struct" or "iddata" format. The Shell Heavy Oil Fractionator (Prett and García, 1988) and Jacobsen-Skogestad high purity distillation column (Jacobsen and Skogestad, 1994) problems are provided as examples for the features of the toolbox; selecting these options in the GUI brings up default parameters that represent sensible choices of design variables for each of these systems.


Multivariable Frequency Response Estimation GUI

File Edit

Loading DATA
Enter Data Structure Array Name (from Workspace) or Click "LOAD ID DATA" for *.mat Files
ıcob_skog_dist_freq

Input Signal Type
● Standard Zippered Signals
○ Modified Zippered Signals
○ Shifted Signals

Analysis and Plot
☑ Frequency Amplitudes
☐ Phases
☐ Time Sequences
☐ Input Power Spectrum
☐ Output Power Spectrum

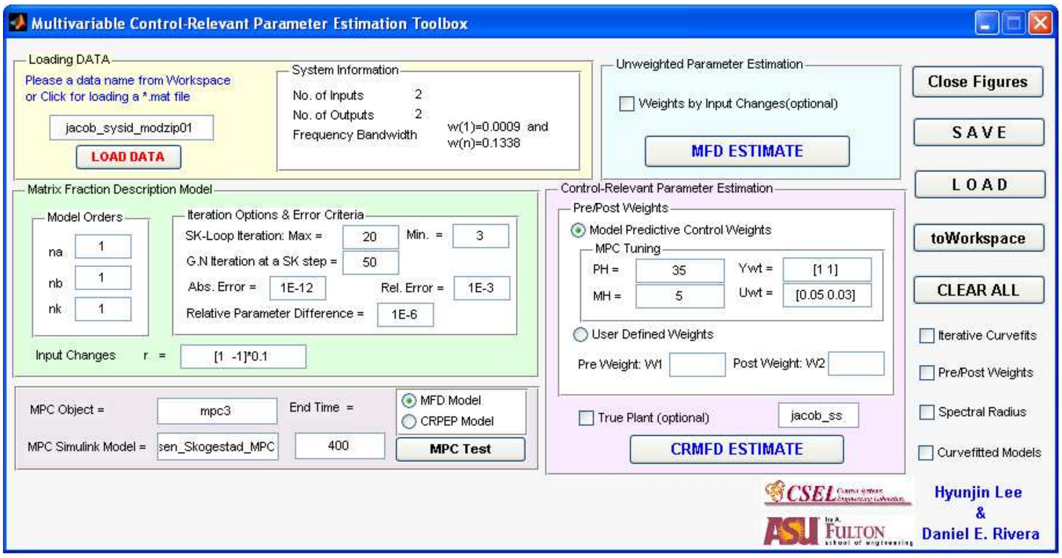
Frequency Response Method
● ETFE analysis
☐ Model-on-Demand Curve Smoothing
○ Power Spectral Analysis
Window Lag =
156 <= 156 <= 916
☐ Conf. Level: s.d. = 99.9%
○ High-order ARX
[na, nb, nk] = [[1:6] [1:6] [1:1]]
☑ Order Selection
Validation Data jacob_val_data
☐ Residual Analysis
☐ Conf. Level: s.d. = 99.9%

Your data [jacob_skog_dist_freq] is successfully loaded and ready for analysis

Fig. 4. Frequency-Response Estimation GUI.

2.2 *Frequency-Response Estimation*

The Frequency-Response Estimation GUI (Figure 4) enables the computation of frequency responses from multisine-generated data using both parametric and non-parametric approaches. The Empirical Transfer Function Estimate (ETFE) and Spectral Analysis (SA) methods are used for non-parametric estimation, while high-order ARX models are utilized for parametric frequency-response estimates. For noisy ETFE responses, a Model-on-Demand curve smoothing algorithm by Stenman *et al.* (2000) is available. The specific requirements created by zippered frequency grids are specially considered for orthogonal ETFE computation; this also includes the



jacob_sysid_modzip01

No. of Inputs 2
No. of Outputs 2
Frequency Bandwidth w(1)=0.0009 and w(n)=0.1338

☐ Weights by Input Changes(optional)

na 1
nb 1
nk 1

SK-Loop Iteration: Max = 20 Min. = 3
G.N Iteration at a SK step = 50
Abs. Error = 1E-12 Rel. Error = 1E-3
Relative Parameter Difference = 1E-6

Input Changes r. = [1 -1]*0.1

● Model Predictive Control Weights
PH = 35 Ywt = [1 1]
MH = 5 Uwt = [0.05 0.03]
○ User Defined Weights
Pre Weight: W1 Post Weight: W2

☐ True Plant (optional) jacob_ss

MPC Object = mpc3
End Time = 400
MPC Simulink Model = sen_Skogestad_MPC
● MFD Model
○ CRPEP Model

☐ Iterative Curvefits
☐ Pre/Post Weights
☐ Spectral Radius
☐ Curvefitted Models

Fig. 5. Control-Relevant Parameter Estimation GUI.

treatment of signals that involve harmonic suppression. Because multisine signals with modified zippered spectra contain correlated frequency grids, an ETFE option is not available; however the SA and ARX estimation options can be used instead.

The GUI takes “iddata” or “struct” format as input data whose essential components include the following: input and output time series, sampling time, cycle length, and number of sinusoids. Once the input data is loaded, the GUI automatically analyzes an input signal type and blocks the choices that are not available with the given input type. Users can export the estimated responses in “idfrd” or “struct” format. These are used in the ensuing modules in support of advanced control system design.

2.3 *Control-Relevant Curvefitting*

The goal of the control-relevant frequency-response curvefitting GUI (Figure 5) is to optimally estimate a useful parametric model with satisfactory control-relevance which can be used as a nominal for Model Predictive Control (MPC). The approach used here follows according to the analysis described in Lee and Rivera (2005*a*; 2005*b*). Users can rely on frequency responses from the previous GUI, or import frequency responses in “idfrd” or “struct” format with the proper syntax. The control-relevant curvefitting algorithm approximates frequency-responses into parsimonious discrete-time state-space model representations based on linear Matrix Fractional Descriptions (MFD) by relying on frequency-dependent pre- and post- weight functions meaningful to MPC control (Rivera and Gaikwad, 1995). The control-relevant weighting functions systematically shift the model error into regions that are less significant to closed-loop control performance. Sanathanan-Koerner iteration and Gauss-Newton minimization are applied to successively improve the model estimate; robustness criteria such as the Small Gain Theorem can be specified from the GUI to monitor the control-relevancy of an MFD model. If a closed-loop Simulink model is available, users can test the estimated model with respect to setpoint tracking directly from the GUI.

3. CASE STUDY

The integrated methodology described in this paper is demonstrated for the strongly interactive distillation column problem according to Jacobsen and Skogestad (1994). The column has an *L/V* configuration and operates at purities of $y_D = 0.99$ and $x_B = 0.01$. Since this process is of 41st-order, control-relevant model reduction is desirable for this system. From open-loop step responses, the dominant time constant range for this system can be estimated as τ^L_{dom}=15 and τ^H_{dom}=194 min. Coupled with user choices of α_s=2, and β_s=3, the GUI leads to acceptable choices of n_s=78, N_s=916, and T=8 min. A directional multisine input with modified zippered spectrum is designed relying on prior knowledge of the steady-state gain; the amplification range suggested by the GUI for correlated harmonics corresponding to the low gain direction $[1 \;\; 1]$ is $64 \leq \gamma \leq 75$. In this example the value γ=72 is used. Figure 6 shows the power spectral designs of shifted, standard zippered, modified zippered multisine input signals generated from the Multivariable Input Signal Design GUI. The three signals are scaled so that the level of uncorrelated harmonics are equal.The corresponding input and output state-space plots are shown in Figure 7; we note in particular that the modified zippered signal is designed to emphasize low gain directionality (e.g., the [1 1] direction) as a result of the geometric directional adjustment intro-

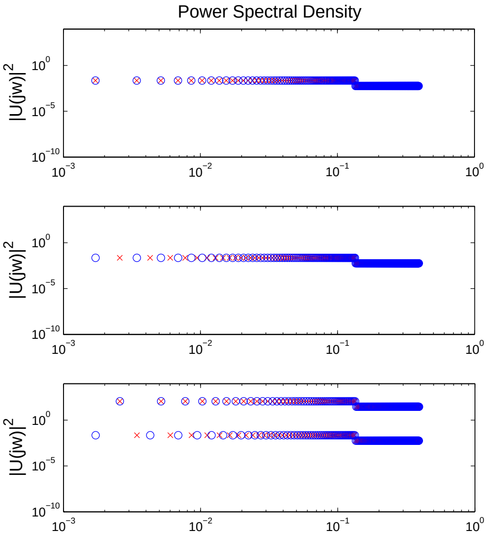


Fig. 6. Input power spectra for shifted (top), standard zippered (middle), and modified zippered (bottom) designs.

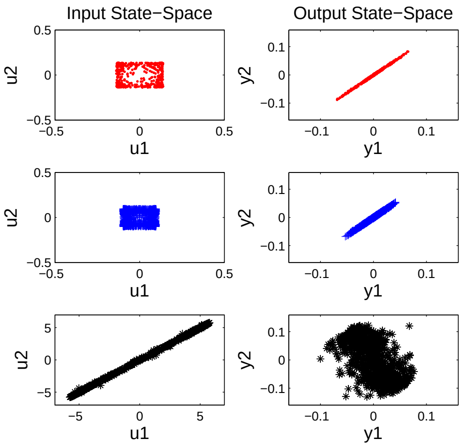


Fig. 7. Corresponding input and output state-space plots: the top is for a shifted design (red), the middle is for a standard zippered design (blue), and the bottom is for a modified zippered design (black).

duced by the presence of correlated harmonics (Lee and Rivera, 2005*b*).

To test the effectiveness of the method under noisy environments, white noise is added to each output channel at $[-1]$ dB in addition to an input disturbance (see Figure 8). The estimated frequency responses are generated using the Frequency Response Estimation GUI as follows: spectral analysis is used for the shifted and modified zippered cases, while ETFE is applied for the standard zippered case. Only the modified zippered case is shown in Figure 9 for the sake of brevity. The frequency responses are exported and loaded into the Control-Relevant Parameter Estimation GUI; unweighted and weighted curvefit models are approximated into low-order matrix fraction description (MFD) models with orders n_a=1, n_b=1, & n_k=1 (see Figure 9).

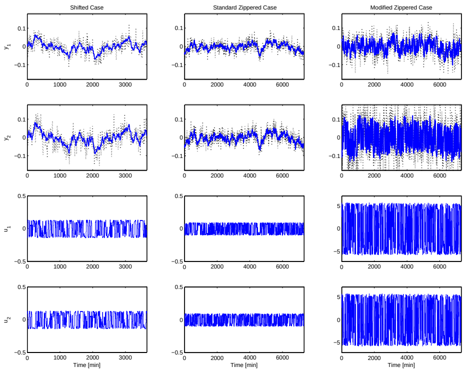


Fig. 8. Time sequences for input and output signals; shifted (left), standard zippered (middle) and modified zippered (right).

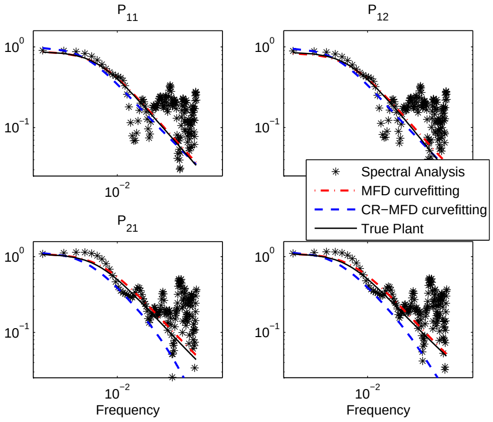


Fig. 9. Control-relevant frequency-response curvefitting for the modified zippered case.

The model adequacy of the curvefitted MFD models for control applications is evaluated in closed-loop setpoint tracking tests using MPC parameters (PH=35, MH=5, Ywt=[1 1], & Uwt=[0.05 0.03]). Although control-relevant weighting properly shifts the model estimation error, the best results are observed from weighted MFD models estimated from the modified zippered case data (Figure 10). The improved low gain directionality in the data results in an estimated low singular value from the model arising from the modified zippered case that is closest to the true plant (see Figure 11). The combination of a sensible input design with the control-relevant curvefitting procedure produces the most suitable model from the data for control purposes, as was reported in Lee and Rivera (2005*b*).

4. SUMMARY AND CONCLUSION

CR-IDENT represents a software implementation of a comprehensive control-relevant identification

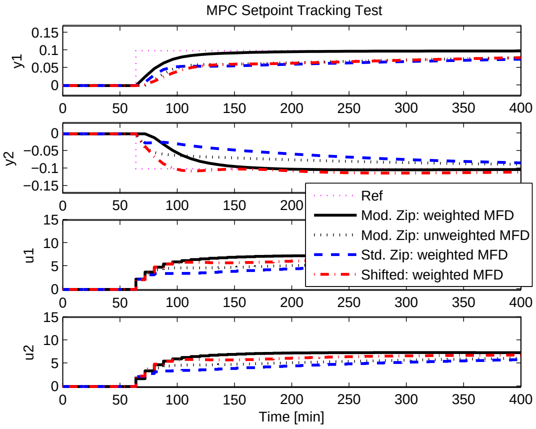


Fig. 10. Setpoint tracking test with MPC for the various curvefitted models.

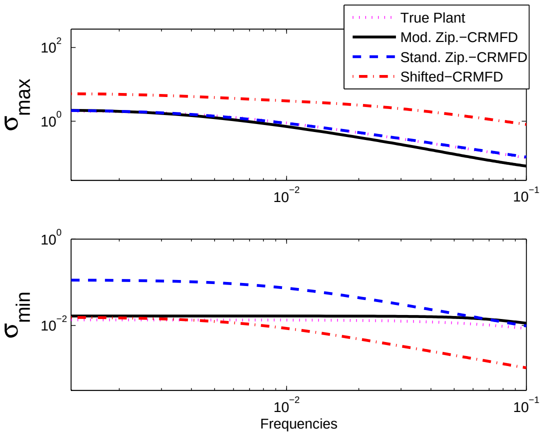


Fig. 11. Estimated singular values vs. the true plant.

methodology that is motivated by the needs and requirements of process systems, particularly strongly interactive ones such as high purity distillation. The toolbox reduces the background and skill level required to implement this procedure, since only *a priori* knowledge of a system in terms of time constants and steady-state gains (if available) is required to initiate this toolbox. Following identification testing, the frequency-response estimation and control-relevant curvefitting modules work interactively (with necessary iterations between the GUIs) to produce a useful model leading to a high performance Model Predictive Controller. This was demonstrated for a strongly interactive distillation column simulation. The most updated CR-IDENT toolbox and its documents can be accessed from the ASU-CSEL website using the link:

`http://www.fulton.asu.edu/~csel/Software.html`

5. ACKNOWLEDGMENTS

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