CLOSID - A Matlab* Toolbox for Closed-Loop System

When identifying dynamical systems with the purpose to use the resulting models as a basis for model-based control design, it can be attractive to do the identification on the basis of closed-loop data.

In this paper a closed-loop system identification toolbox for Matlab is presented, including a user-friendly graphical user interface.

The toolbox is written as an add-on to MathWork's System Identification Toolbox (SITB), version 4.0, and suited for Matlab version 5.2.

With this CLOSID toolbox it is possible to identify linear models on the basis of experimental data obtained from a plant that is operating under the presence of a controller.

It comprises several closed-loop identification methods (both classical and more recent ones), and includes tools for evaluation of closed-loop model and controller properties.

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1 Introduction

Many industrial processes operate under feedback control. Due to unstable behaviour of the plant, required safety and/or efficiency of operation, experimental data can only be obtained under so-called closed-loop conditions.
This applies not only to many industrial production processes like e.g. paper production, glass production, and chemical separation processes like crystallization, but also to mechanical servo systems as robotic manipulators and high precision motion control systems in e.g. audio and CD-ROM disc drives.
Besides, many processes in non-technical areas, as e.g. biological and economic systems, involve inherent feedback loops that can not be manipulated and/or removed. Identification methods for dealing with closed-loop experimental data have been developed in the seventies and eighties, see [5] for an overview.
These "classical" methods are typically directed towards solving the consistency problem, considering the situation that plant and disturbance model can be modeled exactly (system is in the model set).

Initiated by an emerging interest in the identification of models that are particularly suitable for model-based (robust) control design, renewed attention has been given lately to the problem of closed-loop identification.
There is a number of arguments to prefer closed-loop experiments over open-loop ones, in case one is interested in model-based control design. These arguments comprise aspects of bias and variance, input shaping, and the fact that a controller can linearize the (possibly nonlinear) plant behaviour in a relevant working point, thus enabling approximate linear modelling.
The question how to determine the plant's control-relevant dynamics, and how to extract them from experimental data is handled in the area "identification for control" of which accounts are given in the survey papers [2],[6].

For the identification of (linear) systems on the basis of experimental data there are well-supported user-friendly tools available.
Next to the commercially available industrial packages as ADAPTx (by Adaptics Inc.), ISID (by ISI) and Tai-Ji ID (by Tai-Ji Control) there is in particular Mathwork's System Identification Toolbox SITB, version 4.0, which is widespread among universities and industries.
In contrast with previous versions this latter toolbox is equipped with a graphical user interface, enabling the user to identify and validate models in different types of model structures by mouse-clicking, rather than by entering (complex) commands.
Additionally there is users' support in terms of graphical tools for model evaluation as well as support for e.g. bookkeeping of identified models.
In the tools that are currently available, there is generally no possibility to include particular knowledge of external excitation signals and/or implemented controllers when the measurement data are obtained under closed-loop conditions.
Besides, it has been motivated in the literature that dedicated closed-loop identification methods can outperform the classical (direct) approach in which the presence of a controller during experimentation is actually neglected.

In this paper a new Matlab toolbox for closed-loop system identification will be presented that extends the functionality of the System Identification Toolbox SITB in the following ways :

- It provides a graphical user interface supported tool for identification of models from closed-loop observations;
- It enables the use of external excitation signals as well as of knowledge of the controller present in the loop;

- It allows the separate identification of plant models and noise models;
- It is written as an add-on tool to SITB, meaning that for the actual estimation part of the closed-loop identification methods, SITB is automatically opened and applied, while in the CLOSID tool the data processing and the (closed-loop) model processing is performed. Therefore full performance and flexibility of the estimation methods in SITB is retained.
- It enables simple evaluation and validation of models in terms of their closed-loop properties, as e.g. closed-loop residual tests, sensitivity functions, complementary sensitivities, closed-loop poles, etc.

In the current version, the graphical user interface of CLOSID supports the graphical display of SISO (single-input, single-output) models only, while the underlying m-files are generally applicable to multivariable processes.

After a short introduction to the basic notions and problems in closed-loop identification, the software tool will be described in more detail. As illustration example its application to an electro mechanical laboratory set-up will be briefly presented.

2 Closed-loop identification

The experimental setup to be considered is depicted in Figure 1.

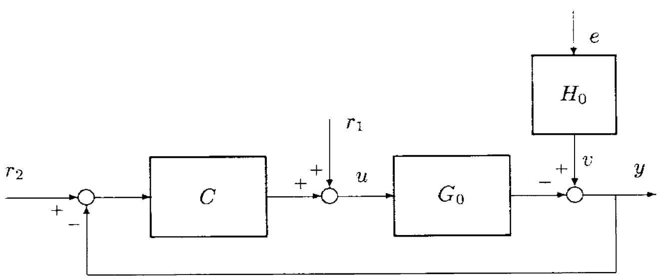

Fig. 1 : Closed-loop configuration

In this configuration r_1 and r_2 are external excitation signals, uncorrelated to the filtered white noise disturbance signal $v = H_0 e$. The sensitivity function of the closed-loop is denoted by $S_0 = (1+CG_0)^{-1}$.

The typical problem in closed-loop identification is the fact that the plant input signal u is correlated with the output noise disturbance v. This is also the reason why a nonparametric (spectral) estimate of G_0, obtained from direct operation on u ad y, will deliver a plant estimate that is a weighted average between G_0 and $-1/C$.

Therefore, for nonparametric estimates of G_0, an external excitation signal r (either through r_1 or through r_2) is required to provide an unbiased estimate of G_0 through $G(e^{i\omega}) : \Phi_{yr}(\omega) / \Phi_{ur}(\omega)$ with $\Phi_{yr}(\omega)$ and $\Phi_{ur}(\omega)$ estimates of the corresponding cross-spectral densities.

In parametric (prediction error) identification three approaches have been followed ([5]) :

- Direct identification, using measurements of u and y only to construct plant and noise models;
- Indirect identification, utilizing knowledge of reference signal and controller to reconstruct a plant model from an estimate of the closed-loop transfer function;
- Joint input/output identification, modelling the multivariable system with r_1 or r_2 and e as input and u and y as output.

A direct identification method utilizes only measured signals u and y, and actually discards information from the closed-loop configuration. Therefore it can be applied by using the standard tools for (open-loop) system identification, as available in the Matlab toolbox SITB.

Its basic property is that plant and noise model can be estimated consistently under weak conditions on the data, provided that a model set is chosen that can exactly represent the real plant and noise characteristics.

However if the chosen noise model is not correct, the plant model will be biased.

The other two approaches (indirect and joint i/o) require knowledge of external excitation signals and possibly controller information.

This additional information enables them to identify plant models and noise models separately, enabling a consistent estimate of G_0 even when the noise model is misspecified.

Additionally it allows a separate validation of G_0 and H_0. CLOSID has particualy been developed to deal with these approaches.

3 Toolbox Set-up

The graphical user interface of the CLOSID toolbox provides a main window as shown in Figure 2.

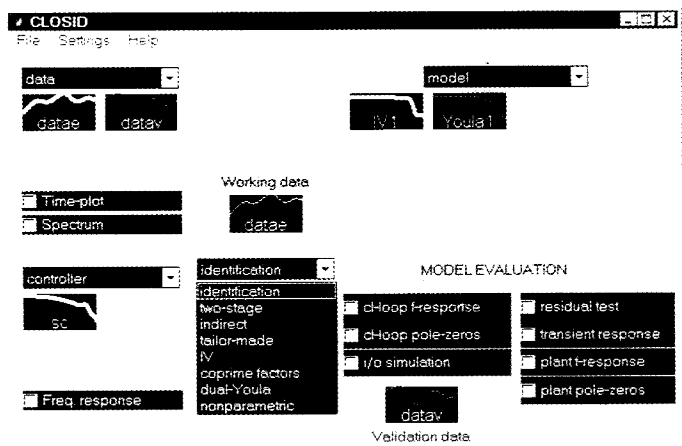

Fig. 2 : CLOSID - Main window

The main window shows the following basic parts :

- a **data board** on the left upper part, where imported data sets are represented by colored line-icons, that can be selected by a mouse action.
- a **controller board** on the left lower part, where imported controllers are represented by colored line-icons, with similar selection options.
- an **identification menu** in the middle; this pop-up menu provides the user with a list of identification methods that can be applied.
- a **model board** on the right upper part, showing identified or imported models of the plant to be identified.
- a **model evaluation** area, containing check boxes for the application of several (closed-loop) evaluation procedures for the models on the model board possibly in combination with controllers selected from the controller board.

Additionally there are selection icons for "working data", reflecting the data that are used for identification, and for "validation data", reflecting the data that are used for all model evaluations.

Besides the controller board, the composition of the CLOSID main window is very similar to the main window of the SITB. This controller board is required, as some of the closed-loop identification methods require information on the implemented controller.

Additionally, this enables the user to evaluate the models in the presence of a (user-chosen) feedback controller.

Data sets, controllers and models can be imported from the MATLAB workspace, through selecting the respective pop-up menus for data, controller and model.

A data set is composed of experimental data $\{u, y\}$ over a given time horizon, together with either one of the external excitation signals r_1 and/or r_2.
Data sets can be viewed on screen in terms of time sequences and power spectra, by clicking on the corresponding check boxes under the data board.
Figure 3 shows the "Data Import" import window, through which data can be imported from the Matlab workspace. Models, as well as controllers, can be imported from and exported to the Matlab workspace, in different formats.

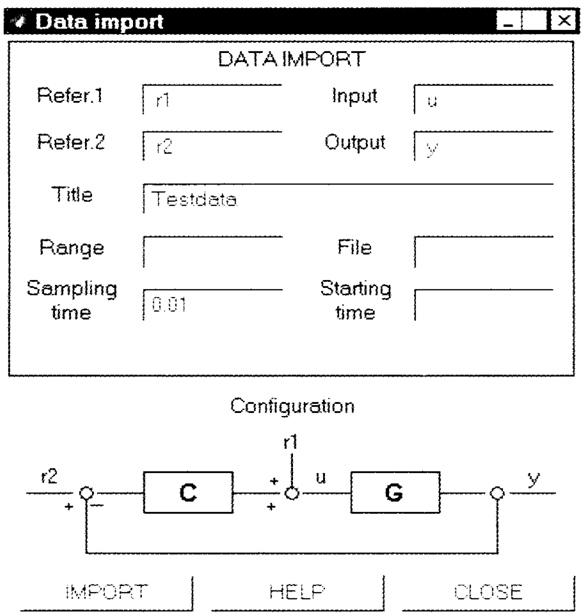

Fig. 3 : CLOSID - Data import window

4 Closed-loop identification methods

The CLOSID toolbox contains six identification methods for parametric model identification, and one nonparametric method.
The methods are denoted by

1. **two-stage** method,
2. **indirect** identification,
3. identification with a **tailor-made** parametrization,
4. **IV** (instrumental variable)-method,
5. **coprime factor** identification,
6. identification in the **dual-Youla/Kucera** parametrization,
7. **non-parametric** (spectral) estimation

For details on the different methods, one is referred to the references, in particular to Van den Hof (1997) and Forssell and Ljung (1999).

The methods are all characterized by three steps, focussed on a specific closed-loop object that is going to be identified.

The three steps are clearly indicated in the several identification windows and are characterized as follows.

- **Construction/selection of auxiliary signals.**
  A first step of choosing - out of the available reference, input and output signals, the appropriate signals for identification of a particular transfer function object.
- **Identification.**
  A second step of actual identification of the considered object, by estimating parameters through a least-squares identification criterion.
- **Calculate plant model.**
  From the identified object a plant model is constructed/calculated and this plant model is copied to the CLOSID model board.

By choosing one of the identification methods from the **identification** pop-up menu, a particular window is opened, displaying the three steps mentioned above.

The first step is trivial for some methods, but requires a separate identification for some others. In these latter cases, quick-start options provide a simple means to construct the appropriate signals.

Apart from the "tailor-made" and the "IV" approach, all parametric identification methods will perform the second step by opening Matlab's SITB automatically, copying the appropriate signals from the CLOSID toolbox to the data board of SITB, allowing the user to identify the required transfer function object in the "open-loop" toolbox. In all of these situations, the second step is an identification problem that can be handled by the algorithms that are available in SITB.

When an appropriate model is identified and validated in SITB, it can be copied to the CLOSID window, by pushing the **Calculate and copy plant model** in the CLOSID identification window.
This third step then transfers the identified object to a plant model on the CLOSID model board, where closed-loop properties of the model can be evaluated. % As an illustration the identification window of the two-stage method is shown in Figure 4.

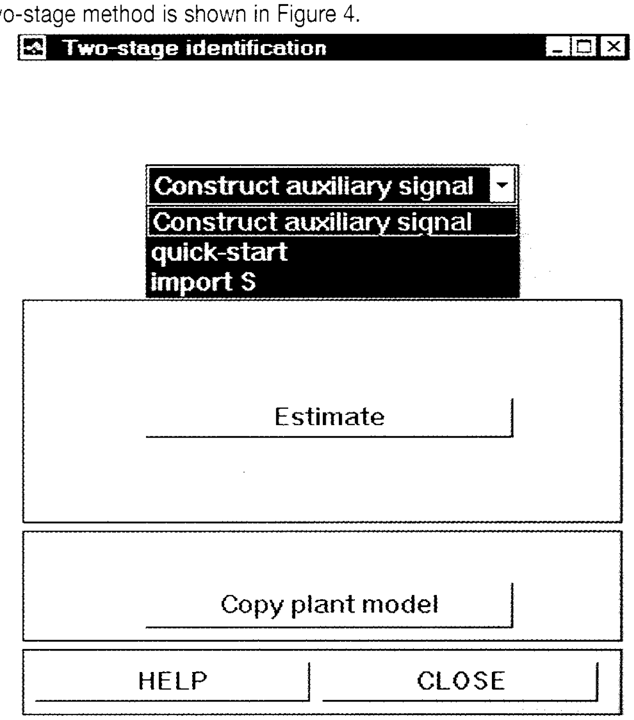

Fig. 4 : CLOSID - Identification window for two-stage identification method

5 Synopsis of identification methods

A brief overview is given of the characteristics of the different parametric methods, and their main properties are listed in Table 1.
Note that all methods require the presence of a persistently exciting reference signal, which can be either r_1 or r_2 (see figure 1).

5.1 Two-stage method

In the first stage the transfer function between reference signal r_1 and input signal u (sensitivity function) is estimated, leading to an accurate (high-order) model $\hat{S}$.
With this estimate a noise-free input signal is simulated according to $x(t) := \hat{S}(q)r_1(t)$.
For this estimation and simulation a quick-start option is available in the toolbox.

In the second stage the noise-free input x is used together with the output signal y to identify a plant model in SITB.

5.2 Indirect method

The closed-loop transfer function between r_1 and y is estimated ($\hat{R}$).
By using information on the implemented controller C, an open-loop plant model is reconstructed from $\hat{R}$, according to

$$\hat{G}(q) = \frac{\hat{R}}{1 - C\hat{R}}.$$

If the controller is stable, then $\hat{G}$ is guaranteed to be stabilized by C. The model order of $\hat{G}$ will generically be equal to the sum of orders of $\hat{R}$ and C.

5.3 Tailor-made parametrization method

The closed-loop transfer function between r_1 and y is estimated, using a dedicated parametrization in terms of the parameters of the open-loop plant model and the known controller C. The plant model $G(q,\theta)$ appears in the closed-loop transfer function as

$$\frac{G(q,\theta)}{1 + C(q)G(q,\theta)}.$$

5.4 IV-method

A basic instrumental variable estimate is constructed using u and y as measured data, and employing r_1 or r_2 as instrumental signal.

5.5 Coprime factor method

The closed-loop transfer functions between (a filtered version of) r_1 and/or r_2 (as input) and (y,u) (as outputs) are estimated, and an open-loop plant model is obtained by taking the quotient of the two estimates.

Using an appropriate filter operation on r_1 and/or r_2 the order of the two objects to be estimated can be minimized.
This filter can be realized on the basis of an auxiliary plant model G_x for which a quick-start estimation procedure is available.

	Direct	Two-stage	Tailor-m	IV	Copr. fact.	indir Dual-Y.K.
Consistency (G, H)	+	+	⌟	-	-	-
Consistency G	-	-	⌟	+	+	+
Tunable bias	-	-	-	-	-	-
Fixed model order	-	-	-	-	⌟	-
Unstable plants	⌟	⌟	+	+	+	+
(G, C) stable	-	-	-	-	-	⌟/+
C assumed known	no	no	yes	no	nc	yes

Table 1 : Main properties of the different closed-loop identification methods; + positive/yes, - negative/no, ⌟ conditional yes.

5.6 Dual-Youla/Kucera method

The closed-loop transfer function between (a filtered version of) r_1 and/or r_2 (as input) and a filtered version of $u + Cy$ (as output) is estimated, creating an object that is stable if and only if the closed-loop system is stable.
By recalculation, an open-loop plant model can be reconstructed. This method is a generalization of the indirect method, being also applicable to situations of unstable plants and/or controllers.

5.7 Non-parametric estimation

The nonparametric identification method identifies spectral models for the one input, two output transfer from r (r_1 or r_2) to $col(y,u)$, and constructs a plant model by taking the quotient of the two scalar nonparametric estimates.

5.8 Overview of properties

Several properties of the different identification methods are summarized in Table 1.
In this table consistency of (G, H) refers to the situation that both plant and noise model can be identified consistently; consistency of G refers to the situation that the plant model can be identified consistently, irrespective of the quality of the noise model estimate.
For some methods it can be indicated with which (frequency-weighted) norm the plant is approximated in case of identification with a reduced order model set.
This property is referred to as «Tunable bias expression». "Unstable plants" indicates whether an unstable plant can be identified consistently.
Methods for which it is possible to restrict attention to identified models of predefined order, are indicated by + in the corresponding row of the table. "(G, C) stable" indicates the property that identified models are guaranteed to be stabilized by the present controller.
Note that for all parametric methods it is possible to also identify noise models for the noise shaping filter H_0.

6 Model evaluation

Once a model is estimated and made available on the model board, several open-loop and closed-loop model properties can be evaluated. This is done using the seven **Model evaluation** options at the right-lower part of the main **Closid** window, figure 2 :

1. **closed-loop transfer** functions. The frequency responses of the four transfer functions from (r_2, r_1), to (y, u), are shown in a separate window, using the current models from the model board and the current controller C from the controller board.
   In the window the amplitude and/or phase of the frequency responses can be shown.
2. **closed-loop poles.** The poles of the closed-loop transfer functions are plotted in a separate window, also showing the stability region (unit circle).
   Thus the (in)stability of the closed-loop system can simply be checked.
3. **input/output simulation.** Using the available reference signal(s) in the validation data set, a plant input signal u and plant output signal y are simulated (noisefree), employing the current model and controller.
   These simulated signals are plotted together with the actual (measured) input and output signals from the validation data set.

4. **correlation test.** The sample cross-covariance function is shown between the external reference signal r in the validation data set, and the output simulation error (top) and the input simulation error (bottom).
   This test indicates whether there is still reference signal information in the output and/or input residual.
5. **transient responses.** Step and/or pulse responses are displayed of the four closed-loop transfer functions from (r_2, r_1) to (y,u), for the current models on the model board and the current controller on the controller board.
6. **open-loop transfer.** The (open-loop) Bode diagram is displayed of the current plant models on the model board.
   This reflects the estimated transfer function between plant input u and output y.
7. **pole-zero plot** of the estimated transfer function between the plant input u and output y.

Selecting one or several of these evaluation tools will open a figure with a plot of the evaluation result for the current models from the model board; where appropriate the current validation data and current controller will also be employed. A zoom option is available in each figure.

7. Example

As an example and for illustrating the facilities of the toolbox, results will be shown of an identification of a laboratory set-up. It concerns a (velocity controlled) motor drive, that drives a flexible shaft, on which two large metal discs are mounted, see figure 5.
As "plant" we consider the transfer between the motor voltage (u) and the angular position (y_1) of the disc on the outer side of the shaft.
The combination of shaft and discs acts as series connection of two second-order systems. As the motor is velocity controlled, the plant contains an integrator in its transfer. For experimenting with the system a stabilizing (PID) controller is implemented.

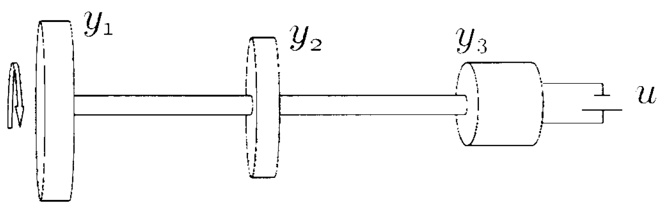

Fig. 5 : Rotating discs laboratory set-up

Experiments are performed in a configuration as indicated in figure 1, where u is the input voltage to the motor, and $y = y_1$ is the angular position of the outer disc.
The closed-loop set-up is excited with an excitation signal r_1 on the motor input, being a pseudo-random binary signal (PRBS). The responses of u and y are measured, and -together with r_1 - used for identification of the plant dynamics.
A data sequence is used with 4096 samples taken with a sampling frequency of 100 Hz. About one third of the data set is not used for identification, but solely for validation purposes.
The signals are indicated in figure 6.

Both a nonparametric and a parametric model are identified on the basis of the measured data.
As method for parametric identification the two-stage method is employed. In its first stage, the quick-start option is used to identify a (high-order) representation of the sensitivity function. In the second stage (applied in the System Identification Toolbox), a 6th order model is identified and preliminary validated.
The frequency responses of non-parametric and parametric model are displayed in figure 7.

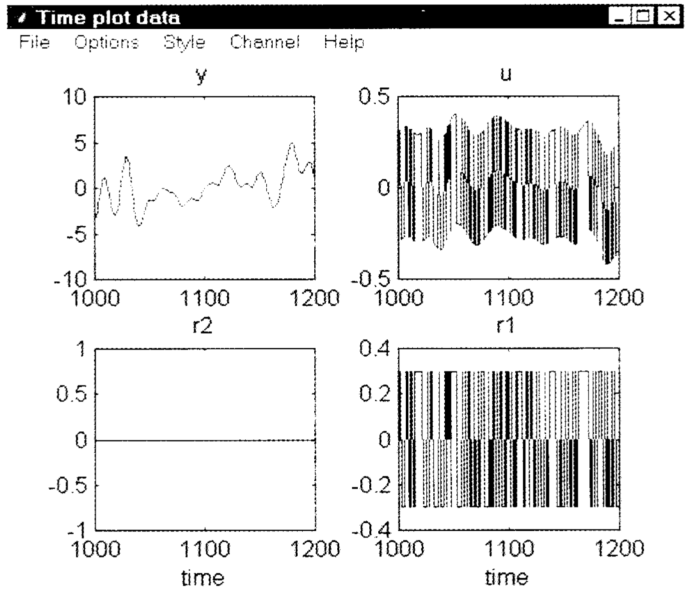

Fig. 6 : Measurement data from a closed-loop experiment

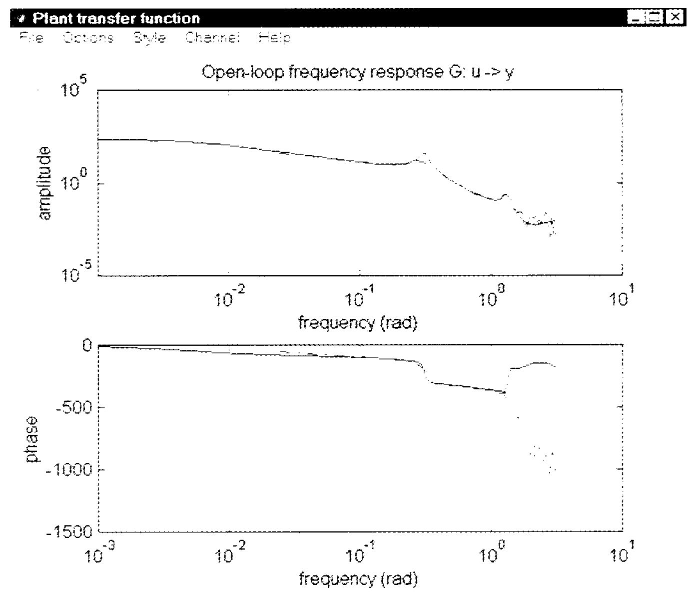

Fig. 7 : Frequency response of non-parametric model (dashed) and 6th order model with two-stage method (solid)

The responses show the integrator behaviour of the plant, and the two moderately damped modes of the flexible system. Both nonparametric and parametric model clearly incorporate these phenomena.
For validation of the parametric model, it is verified whether the input and output residual signals of the closed-loop model are correlated with the (external) reference signal.
Results of this test are depicted in figure 8.

It appears that the correlation remains clearly within the confidence bounds, indicating that there is no evidence in the data to reject the current model.
Closed-loop properties of the identified models can be investigated, e.g. by evaluating the several closed-loop transfer functions.
Figure 9 shows an example of the closed-loop plots that can be made available.

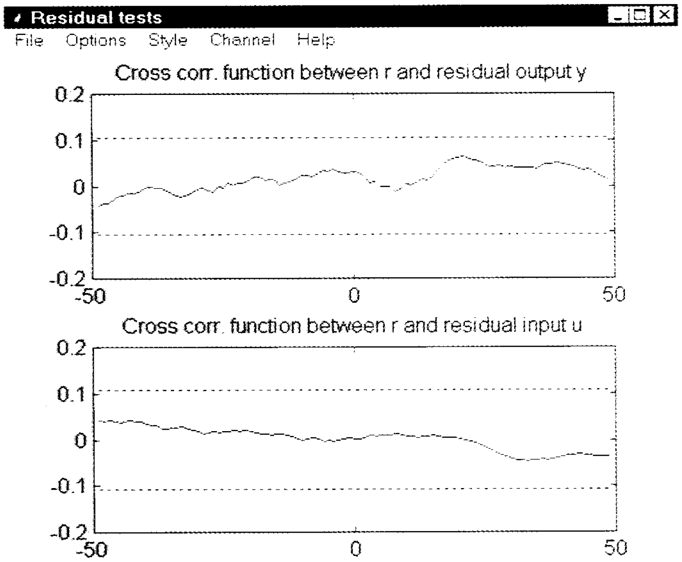

Fig. 8 : Closed-loop residual test for the 6th order parametric model identified with the two-stage method

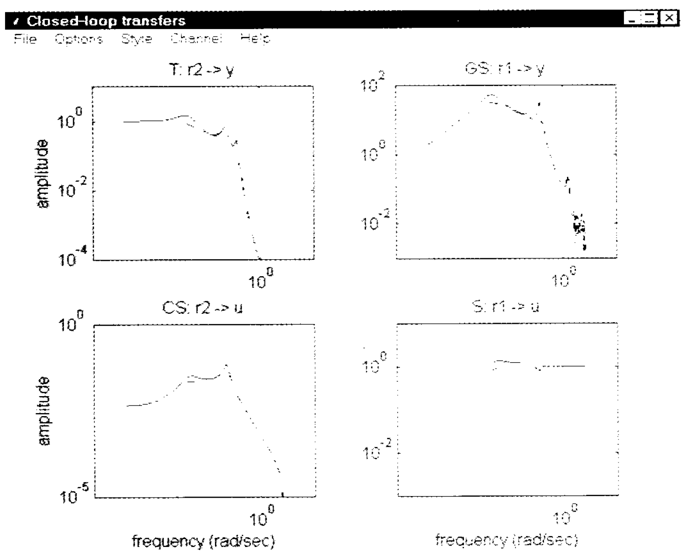

Fig. 9 : Closed-loop transfer functions of nonparametric model (dashed) and 6th order model identified with two-stage method (solid)

8 Summary

A MATLAB toolbox has been presented for closed-loop system identification on the basis of time domain data. It has been designed as an add-on to Mathworks' System Identification Toolbox (SITB).
A graphical user interface with a lay-out similar to the SITB supports the user, and facilitates exchange of models between the SITB and the current toolbox.
In its current version the graphical user interface supports the identification of SISO models; the provided MATLAB m-files are implemented to handle also multivariable models. The tool is available to the public domain at the web-site www.wbmt.tudelft.nl/sr.

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