CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH

7.1 INTRODUCTION

From the current practice it is concluded that the open-loop step testing approach, which is typically used for process identification in Model-based Predictive Control (MPC), has a number of disadvantages. The closed-loop system identification (SID) approach is less intrusive than the open-loop SID approach and may reduce re-identification time considerably. The ability to identify the process model while the existing MPC controller is operating will mean that safety, product quality and optimality requirements are met.

In this work, for the above-mentioned reasons, multivariable closed-loop SID for use in MPC was studied. The approach to the research project was to, first, review all the relevant closed-loop identification techniques. Second, the most appropriate closed-loop SID methodology for plants controlled by MPC controllers was chosen. Third, simulations were used to validate this methodology. Fourth, the methodology was employed to identify part of the MIBK plant from real process data, and a known process model was compared to the identified model. Lastly, the implemented methodology was evaluated by inspecting the results obtained from these simulations in Chapter 6 and the experiment in Chapter 7.

The conclusions reached after these four stages are now discussed. The conclusions arrived at after the third and fourth stages of the research approach are also an evaluation of the proposed methodology.

7.2 REVIEW OF THE CLOSED-LOOP TECHNIQUES

From the available closed-loop theory it is concluded that the basic problem with closed-loop data is that it is, typically, less informative about the open-loop system and that many estimation methods fail when applied in a direct way to closed-loop data, because of the correlation between the noise and the input to the plant. It is concluded that the prediction error method (PEM) applied in the direct fashion, with a noise model that can describe the true noise properties, still gives consistent estimates and optimal accuracy. Therefore, the PEM method was chosen for the proposed methodology.

The *identifiability* analysis shows that the open-loop condition for informative experiments, namely that the input should be persistently exciting (PE) of sufficiently high order, does not ensure identifiability in closed-loop. It is concluded that, in closed-loop, the spectrum of that part of the input that originates from the reference signal should be non-zero. This means that there should be either a nonlinear relationship between the input and the output or the reference signal should be PE.

From the identifiability analysis of the new *inter-sampling method*, where the plant output is sampled at a higher rate than the control input, it is concluded that this approach can also ensure identifiability.

The review of the available bias and variance analysis of the different approached lead to the following conclusions:

Bias: In the direct approach a bias will result, if the noise model cannot describe the true noise properties. This bias will be small in frequency ranges where either or all of the following holds: the noise model is good, the feedback contribution to the input spectrum is small, and the signal-to-noise ratio (SNR) is good. However, the indirect and joint input-output approaches can give unbiased estimates of $G_0(e^{i\omega})$, even with a fixed noise model.

Variance of Estimated Transfer Function: The asymptotic variance of the estimated transfer function is equal for the direct, indirect and joint input-output approaches, if the feedback is linear. However, this variance is worse than the variance obtained in open-loop SID, since the denominator of the variance expression contains only the spectrum of that part of the input that originates from the reference signal, while the open-loop expression has the total input spectrum in the denominator.

Variance of Parameter Estimates: When the asymptotic variance of the parameter estimates, i.e. the finite model order case, is considered, the direct approach is optimal, since it meets the Cramèr-Rao bound. The other closed-loop approaches are less precise, since they do not meet this bound.

7.3 Selection of a Methodology Applicable to MPC Controlled Plants

It is apparent from the relevant literature that there are many options available, regarding identification approaches, guarantees of identifiability, model structures and model validation techniques. From all the options the most appropriate ones were chosen for the proposed closed-loop identification methodology for MPC controlled plants. These choices are mainly based on: the theory regarding closed-loop SID; characteristics of MPC controllers; characteristics of industrial plants; keeping the methodology relatively uncomplicated; and results from similar cases.

Closed-Loop SID Approach: The direct closed-loop SID approach was chosen, since this approach is applicable to systems with arbitrary feedback mechanisms and it ensures consistency and optimal precision. Furthermore, it simplifies the development of the methodology, because it makes use of the standard functions in the MATLAB system identification toolbox and does not require any custom-written algorithms or extra software. Thus, it is not necessary to develop any new closed-loop SID software.

Guarantee of Identifiability: It is concluded that a PE reference signal should be used in order to guarantee identifiability. The changes in a multivariable MPC structure, as it deals with changes in the active constraints, are unpredictable under normal operation and can thus not guarantee a given number of changes in the controller settings. Therefore, although MPC controllers are nonlinear, time-varying and complex, which in general yield informative experiments, this should not be taken as a guarantee for identifiability. The option of *inter-sampling* the plant output to ensure identifiability was also considered. However, from the variance simulation study it is concluded that, without structured tests that ensure good SNRs, a model identified with this approach has unsatisfactory precision.

Model Structure: It is concluded that the ARX type model structure is the best choice of model structure, provided that the noise model is accurate for the process to be modelled. The reasons being: it utilises the numerically simple and reliable least square estimation (LSE) method that is a PEM estimation method and is thus consistent in closed-loop; it is parametric, which ensures compactness and accuracy; it can handle unstable systems, since it has a stable predictor; and MATLAB allows for MIMO model estimation of ARX structures.

Model Validation: It is concluded that the standard validation tests used in open-loop SID should also be used to validate closed-loop identified models. Furthermore, it is concluded that the methodology should be validated by comparing the closed-loop identified models to the open-loop identified models and by doing an examination of the closed-loop systems. The validation methods, summarised in Sections 4.8.5 and 4.8.6, were chosen. Together with these methods, a measured closed-loop validation data set is used.

The proposed methodology is further summarised in terms of the five SID steps in Section 4.8.

7.4 Validation and Evaluation of the Methodology with Simulations

In the simulation study a multivariable plant, controlled by an MPC controller, was identified from simulated closed-loop data. In order to evaluate the consistency of the identification methodology, the plant was identified for different settings in the controller as well as for different added disturbances. Different methods to ensure identifiability were also considered.

From these simulation results, it is concluded that the proposed closed-loop system identification methodology gives reliable results, i.e. accurate and precise models, for multivariable plants controlled by MPC controllers, for the type of system disturbances and constraints used in the simulation, as long as the reference signals are PE and the SNRs (ratios between noise and plant input signals) are good.

It is concluded that when PE reference signals are used, the proposed closed-loop SID methodology and open-loop SID method deliver comparable identification results. When the reference signals are not PE, or when they result in bad SNRs, the methodology should be reconsidered. Other methods that ensure identifiability, e.g. inter-sampling and nonlinear controllers, also do not guarantee precise models, if the SNR is not good, which is possible when no structured tests are performed.

Structured tests should be conducted to ensure good SNRs, and the easiest way to ensure identifiability is to make the reference signals PE.

7.5 Validation and Evaluation of the Methodology with Real Process Data

A part of a reactor, which is part of the multivariable MIBK plant at Sasol, which was designed to produce MIBK from the feedstock DMK, was chosen for the validation of the chosen closed-loop SID methodology. No structured tests could be performed on the plant. Thus, logged data sets from normal operation were used instead. Only the input and output signals of the plant were known. The reference signals, as well information regarding the controller settings, the noise and the disturbances, were not available.

Unfortunately, it is concluded that the available open-loop identified model is not a good representation of the plant in closed-loop operation at the relevant time, since the open-loop identified model is not able to satisfactory reproduce the measured closed-loop data. Therefore, not much could be learned from the validation tests where the open-loop and closed-loop identified models are compared.

From the standard validation tests, it is concluded that an unsatisfactory model for controller design was identified from the data measured under normal closed-loop control. The most probable reason for this is that, although the data were informative enough, since it was inter-sampled, the reference signals were probably not PE and the SNRs were not good, which resulted in an undesirable large variance in the closed-loop identified model.

From this experiment a preliminary conclusion is that an unsatisfactory model will usually be identified from data measured under normal closed-loop control, because when structured tests are not performed PE reference signals and good SNRs are not guaranteed.

7.6 Direction of Future Research

Much more research is needed on the challenging topic of closed-loop system identification. Especially, in model validation, the quantification of the model errors in a form that is more suitable for controller design is still an open research question [3].

Closed-loop identification techniques can also be used in MPC controller monitoring and maintenance [3]. When sufficient industrial experience of closed-loop identification is obtained, the next logical step is adaptive MPC.

An adaptive MPC technique, called MPCI, has already been proposed. The basis philosophy of MPCI is the inclusion of PE constraints in on-line optimisation. In the technique, proposed by Nikolaou and Eker, process outputs are free to move away from set-points, as long as they remain within specification bounds. Process inputs, on the other hand, are constrained to excite the process as much as possible, for the generation of maximum parameter information, while process outputs violate specification bounds as little as possible. There are many facets of MPCI that still need to be studied, along the lines of the rich literature on SID [48].

As mentioned, only a preliminary conclusion can be made from the experimental results, namely that structured tests that ensure informative experiments are needed to ensure successful implementation of the proposed closed-loop SID methodology. Therefore, in future, structured tests, with PE reference signals, on a real process are needed to validate the results obtained in the simulation study, namely that structured tests are needed.

When the necessity of PE reference signals has been shown, it will be desirable to do further studies on implementation of MPCI, where the PE condition is included in the online optimisation.