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EXPERIMENTAL MODELING OF NO_X EMISSIONS IN MUNICIPAL SOLID WASTE INCINERATOR

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Abstract: The problem of experimental analysis and modeling of nitrogen oxide emissions in a municipal solid waste incinerator is addressed in this paper. Identification of a continuous-time model from input/output data is presented here as an alternative to physical modeling. Identification results are discussed and cost effective propositions are made to achieve reduction of nitrogen oxide emissions in municipal solid waste incinerators by improving the air feeding control system. *Copyright ©2002 IFAC*

Keywords: Continuous-time model; Grate combustion furnace; Environmental system; Industrial application; Municipal solid waste incinerator; Nitrogen oxide emissions; System identification

1. INTRODUCTION

Municipal Solid Waste (MSW) incineration with grate combustion furnace is a well established reliable and economic method to convert waste to nonharmful products, and to reduce waste disposal. Due to the continuously changing waste composition and heating value, MSW incineration is one of the most complex industrial processes presently in use. In order to improve the design of MSW Incinerators (MSWI), worldwide large research programs have been performed, using physical modeling techniques and experimental investigation on full-scale and pilot-scale equipment in UK (Nasserzadeh *et al.*, 1994), The Netherlands (Van Kessel and Hem, 1995), Sweden (Dong, 1998), Switzerland (Olsommer *et al.*, 1997), and France (Laboulle, 1996).

More and more stringent regulations are established to reduce air emissions and to improve residue quality from waste treatment facilities. The concentrations of certain pollutant components in the flue gas like SO_2, HCl or Hg can

The present experimental modeling study has been undertaken by the Centre de Recherche en Automatique de Nancy (CRAN), the Centre de Recherches sur l'Environnement, l'Energie et le Déchet (CREED, Onyx - Vivendi) and the Agence De l'Environnement et de la Maîtrise de l'Energie (ADEME), for improving the understanding of NO_x emissions in a full-scale MSWI with grate combustion furnace.

only be slightly influenced by changing combustion conditions. These components have to be removed from the flue gas by a cleaning unit. Concentration of other gaseous pollutant components as CO, and nitrogen oxides NO_x can be reduced by optimizing combustion conditions. Due to a considerable amount of chemically bound nitrogen in the waste and locally high temperature in the furnace, NO_x concentrations in flue gas of MSWI are significantly higher than those of fossil-fuel power plants. NO_x emission limits of 300 to 500 mg/Nm^3 at 11 % O_2 dry are typical, where the NO_x concentration corrected at 11 % O_2 is computed from the measured NO_x and O_2 concentrations as follows :

$$A_{NO_x\,11\%} = A_{NO_x} \frac{21 - 11}{21 - A_{O_2}}. \qquad (1)$$

It has been reported that NO_x have harmful effects on animal and plant life (Elichegaray, 2001). A recent new European directive on waste incineration (EC, 2000) limits the NO_x emissions to 200 mg/Nm^3 at 11 % O_2 dry, for MSWI whose load exceeds 6 tons of waste per hour, from December 28^{th} 2005 on. An attempt to explain the chemical mechanisms that form NO_x in combustion is presented in (Stoffel and Riccius, 1999). Based on this knowledge, primary techniques for improving the air distribution and combustion control, represent a highly cost effective way of reducing NO_x formation. However to meet the daily average NO_x emission limit of 200 mg/Nm^3 at 11 % O_2 dry, secondary techniques are necessary. These abatement techniques reduce the NO_x produced by the combustion process. They rely upon the injection of a reagent to reduce the NO_x to nitrogen and water. However, it has been shown on full-scale equipment (Jorgensen and Madsen, 1999; Scutter *et al.*, 1999) that combining primary and secondary techniques offers the advantage of reduced reagent consumption costs.

To obtain an accurate mathematical representation of NO_x emissions, classical approaches use fluid dynamical modeling, which requires a good physical knowledge of the process. They are based on balance equations and lead to complex models, often inappropriate for control design. Process identification represents an alternative to this physical modeling. Different model identification approaches have already been applied to predict fossil-fuel (Adali *et al.*, 1998; Liu and Daley, 2001) and MSW-fuel (Matsumura *et al.*, 1998) NO_x emissions.

This paper describes the first results of the practical application of continuous-time model identification techniques (Sinha and Rao, 1991; Garnier and Mensler, 2000) to model NO_x emissions. The aim is here to analyze the effect of manipulated variables of the process on NO_x emissions and to estimate a linear dynamical model of these emissions from experimental data. The paper is organized as follows. The plant is described in section 2. Section 3 is then devoted to the identification procedure and results. Pieces of discussion and interpretation are finally given in section 4.

2. PLANT DESCRIPTION

2.1 *Description of the MSWI*

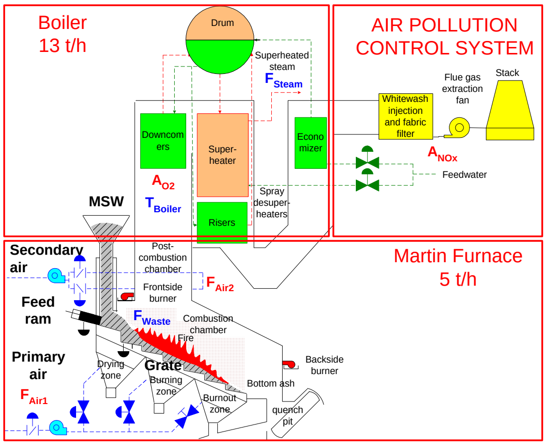


Fig. 1. MSWI with grate combustion furnace

Experiments were performed on a MSWI with grate combustion furnace. The plant is organized into three classical subsystems, depicted on figure 1: a furnace, a boiler and an Air Pollution Control System (APCS).

The furnace has been designed by Martin to burn 5 tons of waste per hour. The waste is introduced on a grate by a feed ram. It is transported on this grate into a drying, a burning and a burnout zone, and agitated. For complete combustion to occur by preventing unburnt materials, air is injected into the furnace in two locations by separate systems: under the grate (primary air or underfire-air) and above the grate to mix additional oxygen with the combustion gases (secondary air or overfire air). Temperature (T_{Boiler}) and oxygen concentration (A_{O2}) of flue gas entering the boiler are respectively controlled by adjusting waste flow (F_{Waste}) and primary air flows (F_{Air1}) entering the furnace.

The boiler is similar to those employed in fossil-fuel power plants. It operates here at a pressure of 34 bar, supplying 13 tons of steam flow (F_{Steam}) per hour at 350 °C for electric power generation.

The APCS employs whitewash injection system for acid-gas (HCl, SO_2), dry powdered activated carbon injection system for dioxin and furan and bag filter for particulate removal. Low amounts of pollutants are emitted in the flue gas. However as there is neither primary nor secondary techniques for reducing NO_x emissions (A_{NO_x}), daily averages of 450 mg/Nm^3 at 11 % O_2 are measured.

2.2 *Waste combustion and NO_x formation*

Waste combustion is a rapid exothermic reaction between waste and the oxygen source in the air. The desired combustion reactions are between carbon (C) and oxygen producing carbon dioxide (CO_2), and between hydrogen (H) and oxygen, producing water vapor (H_2O). Incomplete combustion of organic compounds in the waste produces some carbon monoxide (CO) and carbon containing particles (e.g. dioxin and furan). The sources for nitrogen-oxygen compounds (NO_x) are the air and the waste feeding the furnace. The portion of NO_x compounds produced from nitrogen with waste origin is called "fuel NO_x", while "prompt NO_x" and "thermal NO_x" are formed with nitrogen from the air. The most important part of NO_x in MSWI with grate combustion furnace has been found to be fuel-NO.

In order to promote complete combustion, oxygen from the air must be injected in the furnace in a greater quantity than the stoichiometric amount. Furthermore, secondary air is injected over the grate to ensure complete combustion of gases. The oxygen concentration should be maintained high enough to ensure complete combustion, yet low enough not to cause excessive NO_x emissions.

2.3 *Overview of the combustion control system*

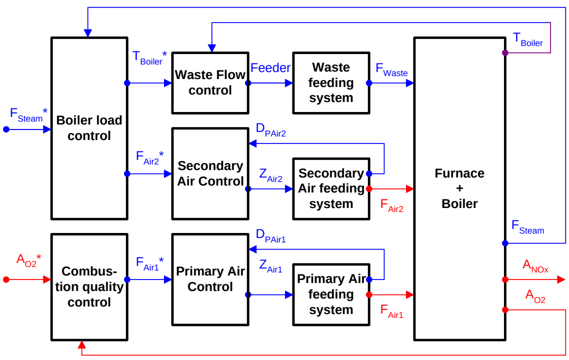


Fig. 2. Hierarchical organization of incinerator control

The hierarchical combustion control system of the MSWI, described on figure 2, consists of cascade and ratio control loops. It can be split up into two main functions.

The first is to regulate a primary controlled variable, the load of the boiler (F_{Steam}) to its set-point (F^*_{Steam}). The master controller generates the set-point of a secondary controlled variable, the flue gas temperature in the boiler (T^*_{Boiler}). The slave controller switches the grate drive and feeder on and off ($Feeder$). The secondary air flow set-point is controlled by ratio F^*_{Steam}/F^*_{Air2}.

The second main function of the control system is to regulate the quality of the combustion to prevent unburnt materials in ash and formation of Products of Incomplete Combustion (PIC) in gases which are CO, dioxin and furan. A master controller regulates the oxygen concentration (A_{O2}) to its set-point (A^*_{O2}), by generating the set-point of the primary air flow (F^*_{Air1}).

3. CONTINUOUS-TIME SYSTEM IDENTIFICATION

3.1 *The identification approach*

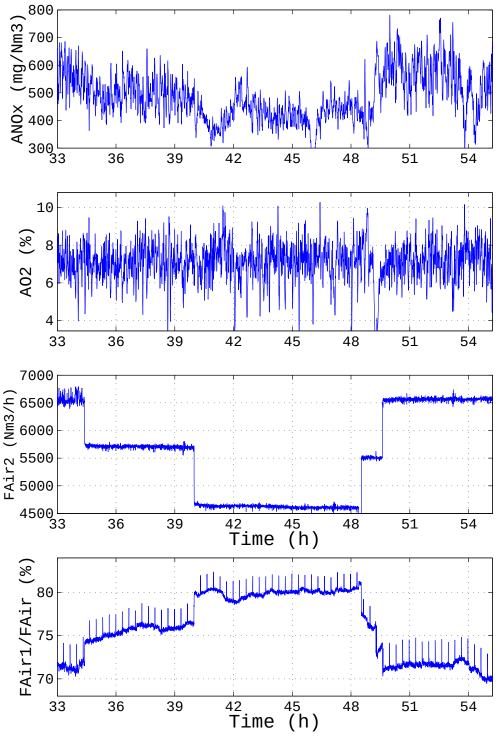
The identification approach presented here consists in reduced order model determination of NO_x emissions from input/output measurements. The industrial process identification problem may be summarized by the following steps (Sinha and Rao, 1991; Ljung, 1999):

- determining the manipulated and controlled variables for the model,
- collecting data of the process, including the design of appropriate excitation signals,
- preprocessing data to remove trends and high-frequency perturbations,
- estimating the model orders and parameters,
- evaluating the final model on its intended application.

These steps are discussed in the following sections.

3.2 *Experiment design*

Three kinds of experiment were carried out while respecting constraints imposed by the industrial company to not perturb the production. The first two experiments consisted in manipulating separately the set-points of the steam flow around 12.7 t/h and of the oxygen concentration in the flue gas around 7.6 %. No sufficiently important effects on NO_x emissions could be observed to follow up these investigations. The third kind of experiments consisted in step of ± 15 %, from 3 to 5 hours long, applied manually on the F^*_{Air2}. Two sets of measurements were recorded, with a sampling period of 10 seconds. Data collection for the first set lasted about 2 days and produced 16000 data samples. We refer to this set as the estimation data set, depicted on figure 3. For the second set, data collection lasted also about 2 days and produced 19500 data samples. We refer to this set as the validation data set.



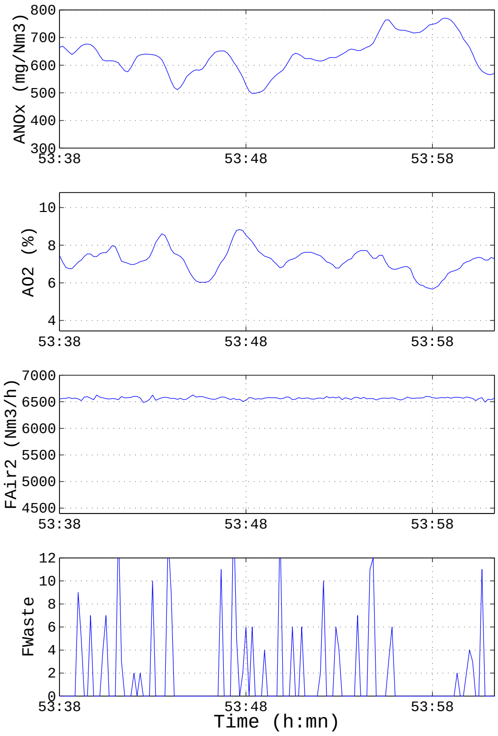


Fig. 3. Part of the estimation data set, recorded from August 6 to August 8, 2001

Fig. 4. Zoomed part of the estimation data set

Combustion analysis of a given amount of waste in a laboratory grate furnace studied by (Jabouille, 1996) have shown the influence of air flows on average NO_x concentration. In the present studied MSWI, the F_{Air1}/F_{Air} ratio is maintained around 70 %, where F_{Air} is the total air flow ($F_{Air1} + F_{Air2}$). The steps on F^*_{Air2} produce variations on the F_{Air1}/F_{Air} ratio, depicted on figure 3. The ratio varies between 70 % and 80 %. The influence of F_{Air2} on A_{NO_x} is clearly noticeable. The figure confirms the result obtained by (Jabouille, 1996) showing that an optimal ratio F_{Air1}/F_{Air} of 80 % leads to smaller NO_x emissions. This is particularly noticeable during the time interval 48-51 h. All the previous comments suggest that the F_{Air1}/F_{Air} ratio might be increased to reduce the NO_x emissions.

Furthermore, under conditions of constant air flows, the waste flow F_{Waste} has an influence on concentrations of both the O_2 and the products of combustion (e.g. CO_2, H_2O). When waste is introduced, O_2 concentration decreases and products of combustion increase. In a MSWI, the boiler load control loop introduces waste by feed ram strokes and grate movements, which leads to variations of the waste flow. The effects of the waste flow variations are visible on both A_{O_2} and A_{NO_x}, as shown on figure 4 where an image of waste flow F_{Waste} has been computed from the measured feed ram position. The action of oxygen concentration control loop on F_{Air1} is far too slow to remove these oscillations, that is why they can be observed on A_{O_2} with a magnitude up to 2 %, but also on A_{NO_x} with a magnitude up to 90 mg/Nm^3.

3.3 *Correlation analysis*

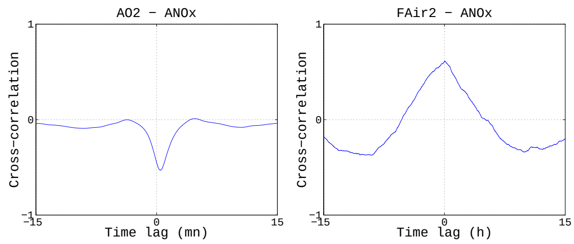


Fig. 5. Cross-correlation characteristics, computed on estimation data set

The cross-correlation functions between A_{NO_x} and the variables A_{O_2} and F_{Air2} have been computed by means of the estimation data in order to check the influence of the combustion air flows and of the waste flow. These correlation functions are depicted on figure 5.

Firstly, the A_{O_2}-A_{NO_x} cross-correlation function has a well defined negative peak at a positive time lag of 70 seconds. Furthermore, the magnitude of the cross-correlation function decreases to zero in a few minutes. It indicates that an increase on A_{O_2} precedes a decrease on A_{NO_x}. It can also be concluded, from figures 4 and 5, that an increase on waste flow produces a decrease on A_{O_2} and an increase on A_{NO_x}.

Secondly, the F_{Air2}-A_{NO_x} cross-correlation function has a positive peak at a positive time lag of 50 seconds. The cross-correlation function decreases to zero in 5 hours, which is the duration of steps on F^*_{Air2}. It can be concluded, from figures 3 and 5, that a decrease on F_{Air2} produces a decrease on A_{NO_x}.

3.4 *Model input/output selection*

From the previous correlation analysis, but also from the process analysis presented in section 3.2, the following Multi Input Single Output (MISO) continuous-time multiple transfer function model between the output variable A_{NO_x} and the chosen input variables A_{O_2} and F_{Air2} will be considered

$$A_{NOx}(s) = \left(G_1(s)\ G_2(s)\right) \begin{pmatrix} A_{O_2}(s) \\ F_{Air2}(s) \end{pmatrix}, \qquad (2)$$

where s represents the Laplace variable.

3.5 *Model order and parameter estimation*

Model order and parameter estimation schemes included in the CONTSID toolbox developed at the CRAN have been used. The CONTSID Matlab toolbox mainly contains time-domain identification methods of continuous-time parametric models for linear time-invariant SISO and MIMO systems operating in open-loop from sampled data (Garnier and Mensler, 2000). It is freely available for academic researchers and can be downloaded from:

http://www.cran.uhp-nancy.fr/cran/i2s/contsid/contsid.html

Very recent extensions for the CONTSID toolbox concern the implementation of the iterative Simplified Refined Instrumental Variable for SISO Continuous-time model identification (SRIVC) first proposed by (Young and Jakeman, 1980) and revisited recently (Young, 2002). Further developments concern the extension of the SRIVC algorithm to the case of MISO systems represented by continuous-time multiple transfer function models based on original works for discrete-time multiple transfer function model estimation (Jakeman *et al.*, 1980). The CONTSID toolbox includes also a routine related to the SRIVC algorithms which allows the user to automatically search over a range of different orders (Young, 2002) to select appropriate orders and time-delays for the model. The very recently developed and implemented algorithms have been used here to select the model order along with to estimate the parameters of the selected model structure.

The main effects on the NO_x emissions are modelled by the following estimated multiple transfer function model $G(s)$,

$$G(s) = \left(\frac{-45e^{-30s}}{1+21s}\ \frac{0.065}{1+116s}\right). \qquad (3)$$

3.6 *Model validation results*

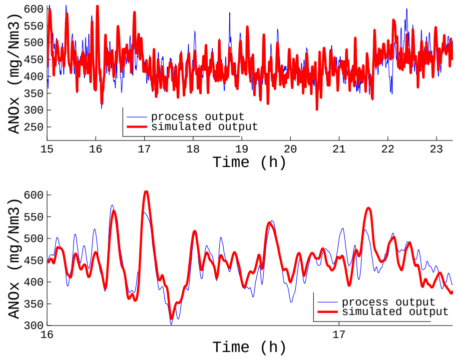


Fig. 6. Validation results

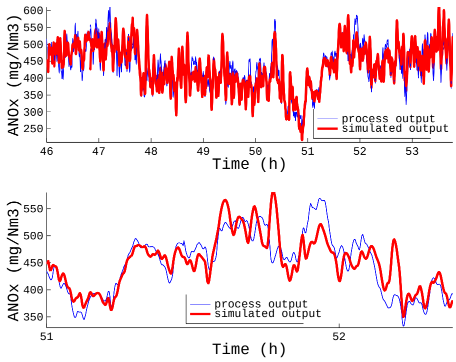


Fig. 7. Cross-validation results

In order to evaluate the model quality, the model output has been simulated and compared to the measured output. Validation and cross-validation results have been computed by means of the estimation and validation data sets and are presented on figures 6 and 7 respectively.

The agreement between the model and the process output is cheering for both validation and cross-validation data sets in the case of these first experimental modeling results. However further developments might be achieved to improve the model quality, as for example to use F_{Waste} instead of or in addition to A_{O2}.

4. CONCLUSION AND DISCUSSION

The application results of the complete process identification methodology to the NO_x emissions of an industrial MSWI have been presented in this paper. The purpose of this experimental modeling procedure was to improve the understanding of NO_x emissions in order to propose cost-effective solutions to reduce them. The effects of the secondary air flow in relation to the F_{Air1}/F_{Air} ratio, as well as that of the waste flow in relation to the feed ram strokes, measured on the oxygen concentration, have been analyzed and identified by a continuous-time MISO reduced-order model.

From the experimental modeling and process analysis, many strategies may now be considered. Results firstly suggest that the F_{Air1}/F_{Air} ratio might be increased to reduce the average NO_x emissions. Secondly, quick variations on O_2 and NO_x concentrations are related to waste flow. The magnitude of these variations might be lowered by improving the introduction of waste in the furnace or by acting on the air flows. The dynamical effect of the waste flow will consequently be analyzed from the control variable of feed ram.

In the case of another combustion control system for MSWI designed by Ansaldo Volund, (Jorgensen and Madsen, 1999) have proposed to use secondary air flow to control small fluctuations in the oxygen concentration, which could then be maintained to a smaller mean value (5.5 %), in order to reduce fuel-NO_x formation. However, despite of these improvements, secondary techniques have remained necessary to achieve European limitations of 200 mg/Nm^3 at 11 % O_2 dry. Nevertheless, these improvements in combustion control have reduced reagent consumption and equipment costs.

5. REFERENCES

Adali, T., B. Bakal, M. Kemal Sönmez and Reza Fakory (1998). NO_x and CO prediction in fossil fuel plants by time delay neural networks. *Journal of Integrated Computer-Aided Engineering, Special Issue on Neural Techniques for Industrial Applications* **6**, 340–350.

Dong, W. (1998). Three-dimensional computer simulation for grate combustion and NO_x emission with a new air supply Ecotube system. Licentiate thesis. Royal Institute of Technology. Stockholm (Sweden).

EC (2000). Directive 2000/76/EC of the European parliament and of the council of 4 december 2000 on the incineration of waste. *Official Journal of the European Communities* **L**(332), 91–111.

Elichegaray, C. (2001). General impact of nitrogen compounds on man and the environment. In: *Internationel Conference on Industrial Atmospheric Pollution - NO_x and N_2O emission control : panel of available techniques.* Paris (France).

Garnier, H. and M. Mensler (2000). The CONTSID toolbox: a Matlab toolbox for CONtinuous-Time System IDentification. In: *12th IFAC Symposium on System Identification.* Santa Barbara (USA).

Jabouille, F. (1996). Contribution à l'étude des facteurs d'émissions des oxydes d'azote lors de l'incinération de déchets ménagers. Thèse de doctorat. Université de Poitiers.

Jakeman, A.J., L.P. Steele and P.C. Young (1980). Instrumental variable algorithms for multiple input systems described by multiple transfer functions. *IEEE transactions on systems, man, and cybernetics* **SMC-10**, 593–602.

Jorgensen, K. and O.H. Madsen (1999). Modern control systems for MSW plants. In: *2nd International Symposium on Incineration and Flue Gas Treatment Technology.* Sheffield University (United Kingdom).

Liu, G.P. and S. Daley (2001). Adaptive predictive control of combustor NO_x emissions. *Control Engineering Practice* **9**, 631–638.

Ljung, L. (1999). *System identification. Theory for the user.* 2^{nd} edition. Prentice Hall.

Matsumura, S., T. Iwahara, K. Ogata, S. Fujii and M. Suzuki (1998). Improvement of de-NO_x device control performance using a software sensor. *Control Engineering Practice* **6**, 1267–1276.

Nasserzadeh, V., J. Swithenbank, C. Schofield, D.W. Scott, A. Loader and A. Leonard (1994). Design optimization of Coventry municipal solid waste incinerator. *Journal of Environmental Engineering* **120**(6), 1615–1629.

Olsommer, B., Y. Duperrex, M.R. Von Spakovsky and J. Van Gilst (1997). Numerical simulation of a natural convection urban waste incinerator. *Rev Gén Therm* **36**, 135–148.

Scutter, J., C. Ostlund and W. Meyer (1999). Techniques for NO_x reduction from MSW combustion plant. In: *2nd International Symposium on Incineration and Flue Gas Treatment Technology.* Sheffield University (United Kingdom).

Sinha, N.K. and G.P. Rao (1991). *Identification of continuous-time systems. Methodology and computer implementation.* Kluwer Academic Publishers.

Stoffel, B. and O. Riccius (1999). Low-NO_x incineration of municipal solid waste in grate systems. In: *2nd International Symposium on Incineration and Flue Gas Treatment Technology.* Sheffield University (United Kingdom).

Van Kessel, L.B.M. and G. Brem (1995). A dynamic model of a municipal solid waste incinerator as a tool for process optimization and operator training. In: *17. Deutscher Flammentag.* Hamburg-Harburg (Deutschland).

Young, P.C. (2002). Optimal IV identification and estimation of continuous-time TF models. In: *15th IFAC World Congress.* Barcelona, Spain.

Young, P.C. and A.J. Jakeman (1980). Refined instrumental variable methods of time-series analysis: Part III, extensions. *Int. J. Control* **31**, 741–764.