Control Engineering Practice 54 (2016) 154–165

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Nonlinear system identification—Application for industrial hydro-static drive-line

Julian Stoev [a,b,*], Johan Schoukens [a]

[a] Vrije Universiteit Brussel, Department ELEC, Pleinlaan 2, B-1050 Brussels, Belgium
[b] Flanders Make, Celestijnenlaan 300, B-3001 Heverlee, Belgium

ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form
8 April 2016
Accepted 14 May 2016
Available online 9 June 2016

Keywords:
System identification
Hydraulics

ABSTRACT

The goal of the paper is to describe the added value and complexities of nonlinear system identification applied to a large scale industrial test setup. The additional important insights provided by the frequency domain nonlinear approach are significant and for such systems the nonlinear system identification is important, for example to estimate the noise and non-linearities levels, which can indicate mechanical and configuration issues. It is not the goal to provide a final full-scale model, but to explore what is the applicability of the nonlinear system identification theories for a complex multi-physical non-academic test-case.

1. Introduction

Many engineering problems require a model of the system. One such example is the design of control logic, which also imposes some requirements on the model structure and simplicity. In many cases the system model can be derived based on physical knowledge about the system. However there are quite often situations when it is not easy to obtain a precise mathematical model in such a way. Even in cases when model equations are available, very often the exact parameters values for the real system are not known. System identification is often used by engineering practitioners in such real-life situations.

1.1. System identification

Depending on the level of the available information the identification procedure is either defined as *white*, *gray* or *black* box identification. White box identification is where the system's dynamics are fully known and can be derived from first principles, but only the parameters values are unknown. Grey box identification involves some knowledge of the dynamics which, when combined with experimental measurements, yields a model. Black box identification is when no knowledge regarding the dynamics is known and an arbitrary model is derived by performing experiments. It is always advantageous to use more of the available physical information about the system, which would correspond to white and gray box models, however it is usually the case that more generic and widely applicable tools are available only for particular nonlinear model structures, which corresponds to black-box models. The identification is also much easier to solve for linear in parameters and/or convex optimization problems, which is not guaranteed in the white-box case.

The field of system identification is now very wide and there are many results, which are of direct practical importance and are used in many industrial projects. The number of control engineers with practical system identification experience is also high, especially taking into account the availability and popularity of several numerical toolboxes, both commercial and freely available. There is now a mature set of tools to solve many practical problems. As in the case of control engineering design, initially linear systems were used for many practical identification problems and the results are obtained by processing them mostly in time domain (Ljung, 1999; Söderström & Stoica, 1988). Many nonlinear systems can be also converted to a linear-like form using different case-specific transformations. More recently, frequency domain methods are also becoming more widespread (Pintelon & Schoukens, 2012; Pintelon, Barbé, Vandersteen, & Schoukens, 2011) due to their advantages with respect to noise, plant operating in closed loop, but also because they permit in a very structural way to give an early estimate about the level of the system non-linearity compared to the linear system dynamics. The main concept is known as the Best Linear Approximation (BLA), which is the linear dynamics approximating best the nonlinear system output in mean square sense. After the non-linearities are evaluated in the frequency domain using BLA and related concepts, they can be modeled in a structured way, which usually is possible only in time domain, for example using the methods in Nelles (2001) and

* Corresponding author at: Flanders Make, Celestijnenlaan 300, B-3001 Heverlee, Belgium.
E-mail addresses: Julian.Stoev@vub.ac.be (J. Stoev), Johan.Schoukens@vub.ac.be (J. Schoukens).

http://dx.doi.org/10.1016/j.conengprac.2016.05.012
0967-0661/

Billings (2013). A particular general class of models, known as Polynomial Nonlinear State-Space (PNLSS), attempts to use in an efficient way the linear BLA fit, obtained using frequency domain methods, to bootstrap the optimization procedure to find the general nonlinear model (Paduart et al., 2010).

1.2. Models used for control design

Designing models, which would be applicable for control engineers in practice, imposes additional constraints on the type of useful models. For example the control theories valid for the general classes of global nonlinear MIMO models are very complex and still actively researched, which makes it very challenging to find the appropriate mature and robust control design procedure (Deng, 2014; Isidori, 1995; Khalil, 2002; Krstić, Kanellakopoulos, & Kokotović, 1995; Nijmeijer & van der Schaft, 2013; Sastry, 2013; Vidyasagar, 1992). The *practical* procedures usually use the "divide and conquer" approach and start by trying to approximate subsystems, design (possibly SISO) controllers for the subsystems, and then connect the controlled subsystems using higher level MIMO controllers (Gasparyan, 2008; Lurie & Enright, 2011). In this work our aim is to find relevant subsystem models, which could be useful at the first step – local subsystem control. This practical approach is also the reason why we do not try to obtain the best model from the point of view of the model error. In the cases when high level of non-linearities is detected, which may represent a challenge from the point of view of control engineers, further exploration is performed what would be the added precision benefits from a nonlinear model. This may be also a point when an informed decision can be made that non-linearities can be eliminated by re-designing, or reconfiguration of the plant.

1.3. Application area – hydraulic systems

One application area where the state-of-the-art system identification appears to be particularly relevant is in the modeling of hydraulic systems (Coen, Paduart, Anthonis, Schoukens, & De Baerdemaeker, 2006; Jelali & Kroll, 2003; Jelali & Schwarz, 1995; Kugi, 2001; Lewis & Stern, 1962; Reuter, 1994; Walters, 2012). Hydraulic systems are typical nonlinear, complex dynamic plants. For this reason, linear model-based controllers that are currently used in practice, quite often do not give satisfying results. Although nonlinear differential equations can describe hydraulic systems, it is difficult to find suitable high performance linear controllers that can easily be implemented on-line. The dynamics of such systems are often time-varying with different time scales, for example dependent on the temperature of the fluid, but also the aging of different elements. The hydraulic part of the system may exhibit a behavior typical for infinite-dimensional systems due to the distributed nature of the fluid in the pipes. The hydraulic part is also difficult to model precisely due to the complex nonlinear relationships, which are often practically approximated as coefficients of static non-linearities, or taken into account as look-up tables which depend on the operating point. Despite these complications, industry has long been attracted and uses the hydraulic systems due to their high force-to-weight ratios (Versteyhe, 2014; Wesolowski et al., 2012). In the same time these systems have disadvantages with respect to the efficiency due to their physical characteristics, but also due to the sub-optimal way they are often controlled.

1.4. Outline and contributions

Contributions: The practical identification procedure has to take into account the effort needed to obtain the system models and the level of technical expertise of the personal involved. The nonlinear models require much more experimental time and much higher level of technical and mathematical expertise. Therefore it is particularly important to estimate if the nonlinear system identification is really necessary from practical point of view. These decisions may have very big effect on the costs and time in the real projects. We present and follow a practical step-by-step procedure, which can deliver as early as possible, information permitting a decision if nonlinear models are needed and later what would be the added benefits of such models.

Outline of the paper: Section 2 gives some background information on the system identification methods we plan to use. In Section 3 some physical insights are provided about the type of non-linearities that are physically present in the test system, followed by experimental results.

2. Proposed procedure

The procedure which is followed has a big influence on the time and efforts which are allocated in the engineering work. Practitioners should take into account that implementing nonlinear identification procedures is a much more challenging task, compared to a linear ones, which are nowadays quite robust and mature. It is also an active field of research and has the potential to remain such for the foreseeable future due to the fundamental mathematical complexities of nonlinear systems. Nonlinear system identification needs more time for the experiments due to the need to cover with experimental data the whole practically important state-space of the system. It also requires higher qualification of the personnel working on the particular task and should be applied only if proven necessary taking into account the control design procedure which will be applied. Linear models are much more common and preferred in the industrial environment, so a very good case should be made if nonlinear models will be needed. Very often after pinpointing the characteristics and the nature of non-linearities, the redesign of the plant is preferred instead of very complex (nonlinear) control design for a highly nonlinear plant. Information should be provided as early, as possible to make the decision if nonlinear modeling will be needed and what are the alternatives in terms of cost and product performance.

The proposed practical work-flow is:

1. Perform a series of specially designed multi-sine experiments that do not take much more time than the classical frequency response measurements.
2. Perform a non-parametric processing of the results to get frequency responses, disturbing noise power spectrum, nonlinear distortion levels. These are fully automatic and with very little user interaction.
3. Make a decision and proceed based on the results in increasing level of complexity and cost:
   (a) Linear modeling is sufficient, because no nonlinear distortions are detected.
   (b) Nonlinear distortions are present, but at a level that they do not hurt (depending on how the model will be used). Linear modeling is performed in the presence of nonlinear distortions.
   (c) Nonlinear distortions are significant (from user point of view), therefore a plant re-design is required, or a nonlinear model is needed. This model can be built either using more detailed physical modeling or using some of the nonlinear system identification procedures.

Remark. The level above which non-linearities are considered *significant* depends in practice on the desired use of the model. If the control engineer can afford to design a linear controller, which