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Nonparametric identification of nonlinear dynamic systems using a synchronisation-based method

Gábor Kenderi [a,*], Alexander Fidlin [b]

[a] *LuK GmbH & Co. KG, Department Calculation, Industriestraße 3, 77815 Bühl, Germany*
[b] *Department of Engineering Mechanics (ITM), Karlsruhe Institute of Technology (KIT), Kaiserstraße 10, 76131 Karlsruhe, Germany*

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ABSTRACT

The present study proposes an identification method for highly nonlinear mechanical systems that does not require a priori knowledge of the underlying nonlinearities to reconstruct arbitrary restoring force surfaces between degrees of freedom. This approach is based on the master–slave synchronisation between a dynamic model of the system as the slave and the real system as the master using measurements of the latter. As the model synchronises to the measurements, it becomes an observer of the real system. The optimal observer algorithm in a least-squares sense is given by the Kalman filter. Using the well-known state augmentation technique, the Kalman filter can be turned into a dual state and parameter estimator to identify parameters of a priori characterised nonlinearities. The paper proposes an extension of this technique towards nonparametric identification. A general system model is introduced by describing the restoring forces as bilateral spring-dampers with time-variant coefficients, which are estimated as augmented states. The estimation procedure is followed by an a posteriori statistical analysis to reconstruct noise-free restoring force characteristics using the estimated states and their estimated variances. Observability is provided using only one measured mechanical quantity per degree of freedom, which makes this approach less demanding in the number of necessary measurement signals compared with truly nonparametric solutions, which typically require displacement, velocity and acceleration signals. Additionally, due to the statistical rigour of the procedure, it successfully addresses signals corrupted by significant measurement noise. In the present paper, the method is described in detail, which is followed by numerical examples of one degree of freedom (1DoF) and 2DoF mechanical systems with strong nonlinearities of vibro-impact type to demonstrate the effectiveness of the proposed technique.

1. Introduction

Identification is a crucial part of developing virtual models of real life systems. Because the computational power of modern computers is increasing exponentially, and related hardware costs are decreasing rapidly, the development of virtual models and simulations is highly attractive to replace czostly physical models and experiments. While for linear systems well-defined frameworks provide straightforward methodologies to solve the identification problem [1], there are

* Corresponding author. Tel.: +49 7223 941 4653.
E-mail address: Gabor.Kenderi@schaeffler.com (G. Kenderi).

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no general solutions for nonlinear systems. A wide variety of approaches exist, each of them having their advantages and drawbacks depending on the specific system of interest. Studies in the field of strongly nonlinear vibro-impact type systems have revealed complex dynamics including chaotic behaviours and bifurcations, which are known to be sensitive to the underlying system model. Hence, the models have to be provided with accurate nonlinear characteristics to investigate system dynamics. These can be, e.g., the nonlinear law of contact friction [2] or the restoring force in the contact defined by geometrical and material nonlinearities [3]. The present study proposes a method for the identification of such characteristics that do not require a priori knowledge of the underlying nonlinearities. In this approach, no discretisation or predefined functional approximation of any type is needed to reconstruct the force-state maps between degrees of freedom.

Decreasing the complexity and costs and increasing the accuracy of measurements are significant challenges in the field of system identification. The development of compact and less costly methodologies for determining system properties is an important trend in mechanical engineering [4]. The presented approach uses only one measured mechanical quantity per degree of freedom, which requires fewer necessary measurement signals compared with truly nonparametric solutions that additionally require displacement, velocity and acceleration signals. The statistical rigour of this procedure can incorporate signals corrupted by significant measurement noise.

In Section 2.1 the identification problem of nonlinear systems is stated in mathematical form for a particular class of mechanical systems considered explicitly in this paper. Sections 2.2 and 2.3 provide brief overviews of known methods for approaching the defined identification problem to which an alternative solution is offered in the present study. This study aims to differentiate the presented approach from the multitude of existing techniques and to note its advantages. The heart of the proposed identification method is the Kalman filter, which is an optimal stochastic observer based on the concept of synchronisation. Section 3 briefly summarises the related theory and describes the main aspects of implementing such observers. In Section 4, the nonparametric identification method is presented in detail and is followed by numerical examples of one degree of freedom (1DoF) and 2DoF mechanical systems in Section 5 to demonstrate the effectiveness of the proposed technique.

2. Overview of identification methods for nonlinear systems

In [5], the identification of nonlinearities is defined to consist of three phases: detection, characterisation and parameter identification. If we think of linear behaviour as a special case of nonlinearity, detection can be perceived as a part of characterisation. However, in some cases the detection can also be treated as a separate process with its own specific techniques. This can be the case of online fault detection or other process monitoring problems. The present study deals only with the 2nd and 3rd phases of the identification of nonlinearities, i.e., characterisation and parameter identification, and does not aim to give solutions to separate detection problems.

The purpose of identification is to extract the highest possible amount of global information from the measurement signals and to assign the gained information to the local system properties. This always implies the assumption of an a priori model of the system. In most cases, the procedure is then carried out by fitting this model to the measurements in the time- or frequency-domain using least-squares or nonlinear optimisation approaches. Other methods, such as the Hilbert–Huang transform and the restoring force surface method discussed in [5], explicitly calculate specific properties of the RFSs using the given model. Whether the a priori model requires the characterisation of the nonlinearities or not decides if the method is called “parametric” or “nonparametric”.

In the following, the identification problem is formulated for a class of mechanical systems that is considered in this paper. This is followed by an overview of the state of the art parametric and nonparametric solutions to the defined problem.

2.1. Problem formulation

For a general nonlinear system, whose dynamics are governed by ordinary differential equations (ODEs), the goal of the identification procedure is to find the vector functions (a and h) of the state vector $\mathbf{x}$ and the input vector $\mathbf{u}$ that define the system consisting of the process Eq. (1) and the measurement Eq. (2) of the form

$$\dot{\mathbf{x}} = a(\mathbf{x}, \mathbf{u}), \tag{1}$$

$$\mathbf{y} = h(\mathbf{x}, \mathbf{u}), \tag{2}$$

where $\mathbf{y}$ denotes the vector of measured quantities with a size of n_y, which defines the number of measurement signals. The present study considers mechanical systems where degrees of freedom are coupled with bilateral connecting forces that are represented by their force-state maps, also known as restoring force surfaces (RFSs). These RFSs can be arbitrary functions of the deformation and the rate of deformation between the two ends of the connections. It is further assumed that the number of these connections is equal to the number of degrees of freedom, which is denoted by N. For mechanical systems described by second-order ODEs, this is half the number of state variables, which is denoted by n. The state vector is defined as

$$\mathbf{x} = \begin{bmatrix} \mathbf{z}_{N\times 1} \\ \mathbf{v}_{N\times 1} \end{bmatrix}, \tag{3}$$