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Sufficient conditions for rate-independent hysteresis in autoregressive identified models

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ABSTRACT

This paper shows how hysteresis can be described using polynomial models and what are the sufficient conditions to be met by the model in order to have hysteresis. Such conditions are related to the model equilibria, to the forcing function and to certain term clusters in the polynomial models. The main results of the paper are used in the identification and analysis of nonlinear models estimated from data produced by a magneto-rheological damper (MRD) model with Bouc–Wen rate-independent hysteresis. A striking feature of the identified model is its simplicity and this could turn out to be a key factor in controller design.

1. Introduction

Hysteresis is a quasi-static nonlinear characteristic found in several mechanical and magnetic systems as in magneto-rheological dampers (MRD), electro-mechanical actuators and sensors, involving memory effects between input and output [13,5]. In mechanical systems, hysteresis is directly related to the inelastic behaviour of joints and materials. Considering magneto-rheological dampers, the hysteresis is related to the magnetic characteristics of the magneto-rheological fluid and also to its mechanical structure.

Due to its strong nonlinearity, hysteresis is not easy to model. Traditionally, phenomenological models have been proposed for modelling systems with hysteresis [13]. One of them is the Bouc–Wen model which was initially proposed by Bouc [7] and extended by Wen [27]. The Bouc–Wen model structure is composed by a first-order nonlinear differential equation, built from physical laws [12] and is able to reproduce several hysteresis loops [10,24].

One of the advantages of phenomenological models is that they are able to incorporate non-local memory effects by including in their structure information about the reversion points [25], as the Preisach model. In systems with non-local memory, the next state on the hysteresis loop depends not only on the current state, but also on the past (non-local) path of the loop.

An important application of models for systems with hysteresis is in control system design. The central idea is to design a controller that implements a model for the system which is able to compensate for the main features of the specific hysteresis loop. In this type of application, it is known that the use of phenomenological models is quite awkward [21] and this

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has served as a strong motivation for developing techniques for identification and control of system with hysteresis [22,5,26,17,14].

In this respect, the use of data-driven models is particularly appealing because the model parameters can be estimated to obtain a model that closely fits the main aspects of a particular hysteresis loop. However, when compared to their phenomenological counterparts, black-box models are generally unable to reproduce certain features as, for instance, the non-local memory effect. Nonetheless to estimate, possibly online and adaptively, models for hysteretic systems to represent the main features of the loop is still a noble goal to pursue. Hence NARX polynomial and neural network models have been proposed for hysteretic systems in [16] and [10], respectively.

The identification of black-box models for systems with hysteresis is not without its own challenges. Probably the greatest one is to determine a convenient model structure in order to stand a chance to represent the main aspects of the hysteresis loop. General algorithms for model structure selection, as the ERR (Error Reduction Ratio), have been developed in the late eighties [15,6]). Unfortunately such algorithms typically do not work well on their own for models of systems with hysteresis.

The main aims of this paper are to discuss the existence of hysteresis in autoregressive models, and to provide sufficient conditions for hysteresis in such models. In order to address these issues, in this paper we introduce the concept of bounding structure of equilibria. The paper also proposes a technique for structure selection for hysteresis models based on term clustering as an effective aid to other regressor selection criteria. Our results show that a very simple autoregressive structure (obtained by the proposed approach) is able to reproduce the main features of an MRD hysteresis loop. Such models can be used, in the future, in model-based control of systems with hysteresis.

Section 2 presents some background material. Sufficient conditions for autoregressive models to reproduce rate-independent hysteresis are given in Section 3. In Section 4 a structure selection procedure is put forwards. Section 4.3 presents the numerical results for the Bouc–Wen model of a MRD. Concluding remarks and perspectives of future research are given in Section 5.

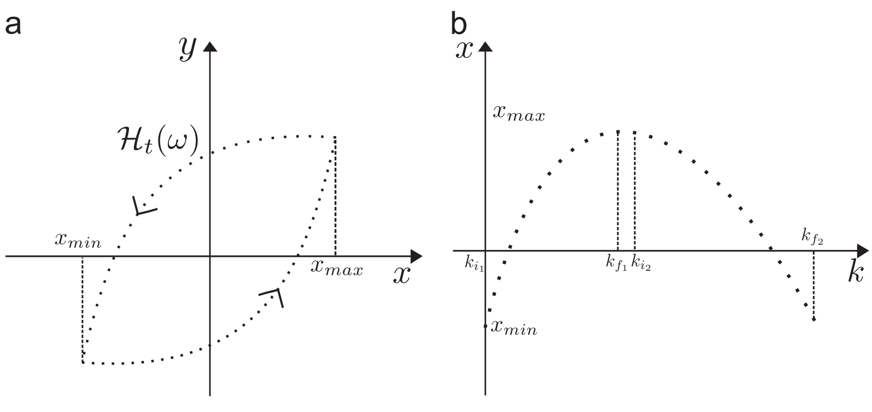
2. Background

This section presents some background material which has been organized as a set of definitions.

Definition 2.1 (*Rate-independent (RIH) hysteresis*). Let $x = A\ \sin(\omega t)$ be the input of a system with hysteresis represented by a closed curve $\mathcal{H}_t(\omega)$ parametrized by the time in the input–output plane. $\mathcal{H} = \lim_{\omega \to 0} \mathcal{H}_t(\omega)$ is here called the bounding structure. If $\mathcal{H}$ delimits the hysteresis loop $\mathcal{H}_t(\omega)$, the system is said to display rate-independent hysteresis (RIH) (Fig. 1).

Remark 2.1. As it will be seen, in the case of RIH, $\mathcal{H}$ is formed by more than one set of equilibria that delimit a region in the input–output plane in which the hysteresis loop $\mathcal{H}_t(\omega)$ is observed. There are systems for which $\mathcal{H}$ will tend to a single set of equilibria as $\omega \to 0$. Such systems are said to have rate-dependent hysteresis (RDH).

One way of modelling RIH is using the Bouc–Wen model. Preisach, Prandtl–Ishlinskii, Duhem and other models can also be used for modelling RIH, as presented in [11]. In this paper we will deal with rate-independent hysteresis (RIH) and use a Bouc–Wen model as a bench test.



Example of hysteresis curve.

Example of a loading-unloading signal.

Fig. 1. Example of hysteresis curve, given a loading–unloading input signal.