



Comparison of restoring force models for the identification of structures with hysteresis and degradation



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ABSTRACT

When subjected to events such as earthquakes, engineering structures typically exhibit a nonlinear and hysteretic behaviour with stiffness and strength degradations. Though a reliable evaluation of safety conditions should take into account the nonlinear dynamic and evolutionary nature of the structural response, the experimental identification of a nonlinear behaviour under dynamic and seismic loading is, to date, an open problem. The present research aims at evaluating the potential of different restoring force models for simulating the seismic response of hysteretic structural systems, with special emphasis on the two main problems encountered when applying this approach to full-scale structures under intense excitation: (a) a markedly time-dependent behaviour; (b) need to compare among different restoring force models, either expressed in a parametric or polynomial form. In particular, polynomial models will be formulated both in terms of restoring force and its derivative, in order to present a comprehensive discussion of different strategies. The nonlinear identification technique employed in this paper is required to account for a time-dependent behaviour. In fact, in presence of degradation or any other time-varying characteristics, instantaneous identification certainly constitutes an enhancement of the classical restoring force based approach, and may as well provide checks on the consistency of the assumed models.

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1. Introduction

Performance based design of engineering structures subjected to dynamic loads calls for expensive experimental tests, whose outcomes, in terms of strength, ductility and dissipation properties, should be assimilated by nonlinear and/or time-varying models. Within the framework of nonlinear structures, the identification process presupposes the availability of a huge quantity of experimental data, much greater than is necessary in linear identification. In this sense, a classification of possible sources of nonlinearity might still retain a practical interest in structural identification, even if the word nonlinearity has a tautological character. Noteworthy reviews exist in literature about nonlinear identification: for instance, the textbook by Worden and Tomlinson [1] and several comprehensive state-of-the-art papers: e.g. [2,3].

A challenging identification case is when parameters to be identified are inherently time-varying (e.g. an instantaneous frequency, degradation in stiffness and/or strength etc.) without a predefined evolution law, which is a situation typically encountered in experimental testing for seismic design. A simple way to check the consistency of a given model consists in

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extracting instantaneous estimates of the model parameters. This may be obtained via standard identification methods applied sequentially on blocks or subsets of the full data in order to detect whether the parameters change slowly with time, or better by applying inherently instantaneous approaches.

Today, the instantaneous identification of the parameters of a system is a suitable way to detect and quantify a degradation or damage. Unfortunately, not all instantaneous approaches admit an on-line or real-time implementation which, for instance, is necessary in structural control. In other words, on-line methods do not require the acquisition process to be completed to perform the identification (see for instance [4]), while off-line methods retain this limitation. For example a joint time–frequency method, despite leading to instantaneous or time-varying estimates, cannot be strictly termed a real-time approach. In fact, at least in theory, the time–frequency uncertainty principle does not allow for an on-line implementation [5,6]. This said, in actual practice the choice of using on-line or off-line predictions depends on the type of transform: for instance, an analysis based on running windows (as in the case of the spectrogram), despite its inherent limitations, can efficiently support an on-line implementation at a low computational cost, unlike a correlative transform structure (e.g. Wigner–Ville transform).

In the time domain, the least squares approach is not always practical for on-line identification of the parameters of a nonlinear system, even if it is possible to find some important examples in literature [7]. Many other identification methods have been investigated: the Extended Kalman Filter (EKF) [8–13], the H_∞ filter [14], or Sequential Monte Carlo (SMC) methods [15–17]. Andrieu et al. [18] state that the advent of SMC, due to good approximation of the optimal filter under weak assumptions, does not mean that SMC is the best candidate for on-line implementations. Indeed SMC methods (also referred as particle filters) suffer from the so-called “degeneracy problem” and are also computationally expensive. Instead, the EKF procedure, which is currently the most exploited, derives from the state-space formulation of the differential equation of motion. The main advantage is that the EKF technique has seen applications in various research fields. In this procedure, the estimation problem is linearised using an extended state space representation of the system. The initial guess is then updated recursively when new observations are available.

Wu and Smyth [4] have successfully applied the Unscented Kalman Filter (UKF) for on-line identification of parameters of hysteretic Sdof systems which both degrade in term of stiffness and strength and pinching. The UKF is a technique which allows dealing with any type of nonlinearity. In detail, differently from EKF, UKF does not require the computation of the Jacobian of the nonlinear function; it does not approximate the measurement equation of the system but it approximates the posterior probability density by a Gaussian density, by using a set of deterministic points (the so-called Sigma points). When the Sigma points are propagated through the nonlinear transform, they capture the mean and the covariance of the system. Xie and Feng [19] proposed to use a further development of the UKF, the Iterated Unscented Kalman Filter (IUKF), for nonlinear and hysteretic springs. In this last case, also 2dof systems with polynomial nonlinearities were investigated. The main advantage of these techniques when applied to hysteretic systems is their capability to deal with any type of functional nonlinearity.

A family of auto-regressive moving average (ARMA) models in the time domain has been recently investigated by Fassois et al. [20,21] who applied them to the identification of time-varying systems. In the same connection, Xiuli and Wang [22] proposed a Gaussian multivariate variation of ARMA model.

The present study will instead retrieve the concept of instantaneous identification with time–frequency representations as already introduced in [5] and applied to nonlinear oscillators in [23,24]. In more detail, this paper employs classical restoring force surface models, but, differently from usual approaches, estimates of the system parameters are extracted instant-by-instant by minimising error functions defined in the time–frequency domain. Instantaneous estimates capture time-varying behaviours and provide an assessment of the pertinence of the chosen restoring force model.

Several models will be examined through numerical simulations: two polynomial models, like the Duffing and a Duffing–Van der Pol oscillator, and the so-called Bouc–Wen hysteretic model with stiffness degradation. For this last model, identification performances associated with a suitable polynomial approximation will be compared to those afforded by parametric approaches. A numerical application to a framed 2dof system under earthquake excitation will be finally presented.

2. Hysteretic models and operators

A model (or operator) may be defined as a relationship between an input (time-) function and an output (time-) function. For structural systems, the input function often is a displacement or a rotation, while the output function usually is a force or a moment. Hysteresis operators are a particular class of operators, characterised by (i) causal memory and (ii) rate-independence [25]. The first property can be explained by the following definition of the output:

$$f(t) = \mathcal{F}(x(\tau)|_{\tau \in [0,t]}, f_0)(t) \quad (1)$$

where t is the current time, τ is the generic time, $x(t)$ is the input function, $f(t)$ is the output function with initial value f_0 , $\mathcal{F}$ is the operator. The above equation states that the output f at the current time t depends on the past input history $x(\tau)$ with $0 \leq \tau \leq t$ and the output value f_0 at $t=0$. A model fulfilling Eq. (1) is said to possess causal memory. The past history dependence implies that the standard restoring force function $f(t) = f(x(t), \dot{x}(t))$ is not single-valued, i.e. for given values of $x(t)$ and $\dot{x}(t)$, several different values of f may occur, according to both f_0 and the past input history $x(\tau)$ for $\tau \leq t$. Conversely,

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