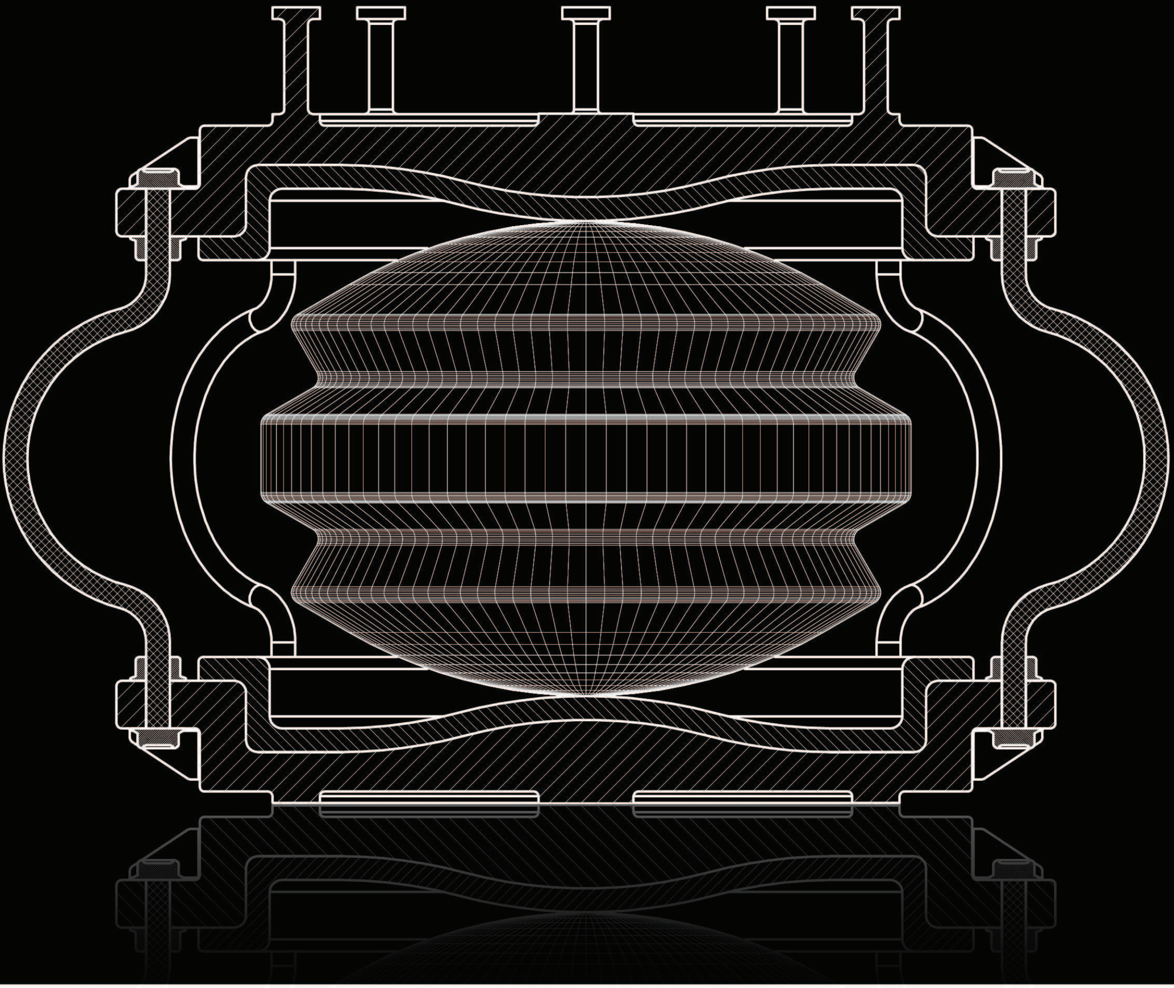
AN INNOVATIVE ISOLATION DEVICE FOR ASEISMIC DESIGN



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Doctoral Thesis

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Conclusions and future work

This chapter concludes the dissertation with a summary of the main contributions and proposes several topics that may be considered for future work. More detailed conclusions have been given at the end of each chapter.

9.1 Contributions

This dissertation aimed to develop a novel isolation bearing that is practical, efficient and has some unique features that are not available in the most commonly used isolation systems. The idea has been realized and the novel isolation bearing is referred to as the roll-n-cage (RNC) isolator. It is a simple passive device that is based on technologies and principles that are universally accepted in practice, just applied in an innovative integrated manner. The major contributions of this dissertation may be summarized as:

- Innovation of a rolling-based isolation bearing that has the following features:

    1. Multi- and unidirectional isolation.
    2. Energy dissipation.
    3. Uplift restraint.
    4. Resistance to wind and minor vibrations.
    5. Built-in buffer.
    6. Inherent gravity-based recentering mechanism.
    7. Suitable for light, moderate and heavy mass systems.
    8. Resistance to flattening of contact surfaces.
    9. Wide range of stiffness and damping.

    10. Independent damping and bearing mechanisms.
    11. Independent stiffness and bearing mechanisms.
    12. Great system-base decoupling.
    13. Non-fixed vibration period.
    14. Expected reasonable construction cost.

- Mechanical characterization of the RNC isolator by means of a computer code in a machine-like environment, which accurately simulates the response of the device subjected to a real testing machine. This allowed the following:
    1. Numerical assessment of the RNC isolator before its construction.
    2. Subjecting the RNC isolator to simultaneous horizontal and vertical loads as in typical practical situations.
    3. Accurate determination of the RNC isolator mechanical characteristics without costly and long-duration testing using real testing machines and actual prototypes.
- Obtaining an input-output mathematical model to describe in a reasonable and manageable form the force-displacement relationship exhibited by the RNC isolator. This allows the following:
    1. Accurate prediction of the RNC isolator behavior.
    2. Performing numerical simulations in significantly shorter runs-time and with no need to huge computer resources.
    3. The possibility of incorporating the RNC isolator into some commercial well known computer codes of structural analysis.
- Mathematical description of the main features associated to rolling of the RNC isolator. This provides the following:
    1. A design tool for the rolling body geometry.
    2. Understanding of the restoring mechanism of the rolling body.
    3. Estimating the RNC isolator resistance to minor vibrations.
- Numerical assessment of the feasibility of the RNC isolator and checking its ability to protect structural and nonstructural systems from seismic hazards through its implementation to a variety of structures having light to heavy masses, in addition to motion-sensitive equipment housed in upper building floors. It is found that:
    1. The RNC isolator reduces greatly the building accelerations, drifts and base shears, while keeping reasonable base displacement. Even when very flexible structures are isolated and long time-period excitations are considered, the proposed RNC isolator is found to be highly effective.

2. The RNC isolation bearing exhibits a robust performance for a wide range of structures, isolator and ground motion characteristics.
3. The RNC isolator is a very efficient tool for seismic protection of motion-sensitive equipment, even via isolation of the entire housing structure or a secondary raised floor, under a wide range of structural properties and earthquake characteristics.

- Presenting an in-depth survey, that contains a review of the past, recent developments and implementations of the versatile Bouc-Wen model of smooth hysteresis, which is used extensively in modeling the hysteresis phenomenon in dynamically excited nonlinear structures. This survey is the first of its kind about the model since its origination more than 30 years ago. The following points have been thoroughly addressed:
  1. Physical and mathematical consistency of the Bouc-Wen model.
  2. Description of the hysteresis loop.
  3. Variation of the hysteresis loop with the model parameters.
  4. Interpretation of the model parameters.
  5. The Bouc-Wen model parameter identification.
  6. Modeling using the Bouc-Wen model.

9.2 Publications

9.2.1 Patents

- Ismail M., Rodellar J. and Ikhouane F. *A seismic isolation system for supported objects.* Patent Number P200802043, Spanish Office of Patents and Marks, 2008 [211].
  - This patent is based on the contents of Chapter 3.

9.2.2 Journal papers

Published

- Ismail M., Ikhouane F. and Rodellar J. The hysteresis Bouc-Wen model, a survey. *Journal of Archives of Computational Methods in Engineering* (2009). Volume 16, Issue2 (2009), Pages 161-188. doi:10.1007/s11831-009-9031-8 [208].
  - Appendix A represents the contents of this paper.

Accepted for publication

- Ismail M., Rodellar J. and Ikhouane F. An innovative isolation bearing for motion-sensitive equipment. *Journal of Sound and Vibration* (2009). doi:10.1016/j.jsv.2009.06.022. [212].
  - This paper is based on Chapter 3 for description, Chapter 4 for modeling and characterization, regarding only the RNC–c isolator, and Chapter 7 for numerical verification.

Submitted

- Ismail M., Rodellar J. and Ikhouane F. An innovative isolation device for aseismic design. *Journal of Engineering Structures* (2009). Submitted [213].
  - This paper is based on Chapter 3 for description, Chapter 4 for modeling and characterization, regarding only both RNC–a and RNC–b isolators and Chapter 5 for numerical verification.
- Ismail M., Rodellar J. and Ikhouane F. Performance of structure-equipment systems with a novel roll-n-cage isolation bearing. *Journal of Computers & Structures* (2009). Submitted [218].
  - This paper is based on Chapter 3 for description, Chapter 4 for modeling and characterization, regarding only the RNC–c isolator, and Chapter 8 for numerical verification.
- Ismail M., Rodellar J. and Ikhouane F. A novel isolation bearing for light- to moderate-weight structures: Theory. *Journal of Earthquake Engineering and Structural Dynamics* (2009). Submitted [217].
  - This paper is based on and Chapter 3 for description and Chapter 4 for modeling and characterization, regarding only the RNC–c isolator.
- Ismail M., Rodellar J. and Ikhouane F. A novel isolation bearing for light- to moderate-weight structures: Numerical assessment. *Journal of Earthquake Engineering and Structural Dynamics* (2009). Submitted [216].
  - This paper is based on Chapter 6 for numerical verification of the RNC–c isolator.

9.2.3 Conference papers

Published

- Ismail M., Rodellar J. and Ikhouane F. A new approach to rolling-based seismic isolators for light- to moderate structures. In *The 14th World Conference on Earthquake Engineering October 12-17, Beijing, China* (2008), No. S25-012 [209].
  - This paper is based on Chapter 3 for description, Chapter 4 for modeling and characterization, regarding only the RNC–c isolator, and Chapter 6 for numerical verification.
- Ismail M., Rodellar J. and Ikhouane F. A new isolation device for equipment protection. In *The 4th European Conference on Structural Control, September 8-12, Saint Petersburg, Russia* (2008), pp. 359–366 [210].
  - This paper is based on Chapter 3 for description, Chapter 4 for modeling and characterization, regarding only the RNC–c isolator, and Chapter 7 for numerical verification.

Submitted

- Ismail M., Rodellar J. and Ikhouane F. An innovative isolation device for aseismic design. In *The 11th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures, November 17-21, Guangzhou, China* (2009). Submitted [214].
  - This paper is based on Chapter 3 for description, Chapter 4 for modeling and characterization, regarding only both RNC–a and RNC–b isolators, and Chapter 5 for numerical verification.
- Ismail M., Rodellar J. and Ikhouane F. Performance of structure-equipment systems with a new isolation bearing. In *The 14th European Conference on Earthquake Engineering, August 30 - September 03, Skopje - Ohrid, Rebuplic of Macedonia* (2010). Submitted [219].
  - This paper is based on Chapter 3 for description, Chapter 4 for modeling and characterization, regarding only both RNC–c isolator, and Chapter 8 for numerical verification.

9.3 Future work

Further research beyond the scope of this thesis is encouraged concerning the novel RNC isolator. It may be particularly interesting to investigate the following lines:

1. Design of a small-scale prototype for the RNC isolator suitable for experimental characterization.
2. Using the designed RNC prototype to experimentally check its validity through buildings and equipment isolation.
3. Checking the feasibility of the proposed RNC isolator for bridges isolation.
4. Design of large-scale prototype, characterization and testing.
5. Preforming cost analysis of the RNC isolator.
6. Influence of the RNC isolator on torsional responses.
7. Comparing the RNC isolator with current isolation systems. ■

A

The Bouc-Wen model, a survey

A.1 Introduction

This chapter deals with the analysis, modeling and identification of a special class of systems with hysteresis. This nonlinear behavior is encountered in a wide variety of processes in which the input-output dynamic relations between variables involve memory effects. Examples are found in biology, optics, electronics, ferroelectricity, magnetism, mechanics, structures, among other areas. In mechanical and structural systems, hysteresis appears as a natural mechanism of materials to supply restoring forces against movements and dissipate energy. In these systems, hysteresis refers to the memory nature of inelastic behavior where the restoring force depends not only on the instantaneous deformation, but also on the history of the deformation.

The detailed modeling of these systems using the laws of Physics is an arduous task, and the obtained models are often too complex to be used in practical applications involving characterization of systems, identification or control. For this reason, alternative models of these complex systems have been proposed. These models do not come, in general, from the detailed analysis of the physical behavior of the systems with hysteresis. Instead, they combine some physical understanding of the hysteretic system along with some kind of black-box modeling. For this reason, some authors have called these models “semi-physical”.

Within this context, a hysteretic semi-physical model was proposed initially by Bouc early in 1971 and subsequently generalized by Wen in 1976. Since then, it was known as the Bouc-Wen model and has been extensively used in the current literature to describe mathematically components and devices with hysteretic behaviors, particularly within the areas of civil and mechanical engineering. The model essentially consists in a first-order non-linear differential equation that relates the input displacement to the output restoring force in a hysteretic way. By choosing a set of parameters appropriately, it is possible to accommodate the response of the model to the real hysteresis loops. This is why the main efforts reported in the literature have been devoted to the tuning of the parameters for specific applications.

The starting point of the so-called Bouc-Wen model is the early paper by [51], where a functional that describes the hysteresis phenomenon was proposed. Consider Figure A.1, where $\mathcal{F}$ is a force and x a displacement. Four values of $\mathcal{F}$ correspond to the single point $x = x_0$, which means that $\mathcal{F}$ is not a function. If we consider that x is a function of time, then the value of the force at the instant time t will depend not only on the value of the displacement x at the time t, but also on the past values of x. The following simplifying assumption is made in [51].

Assumption 1 *The graph of Figure A.1 remains the same for all increasing function* $x(\cdot)$ *between* 0 *and* x_1*, for all decreasing function* $x(\cdot)$ *between the values* x_1 *and* x_2*, etc.*

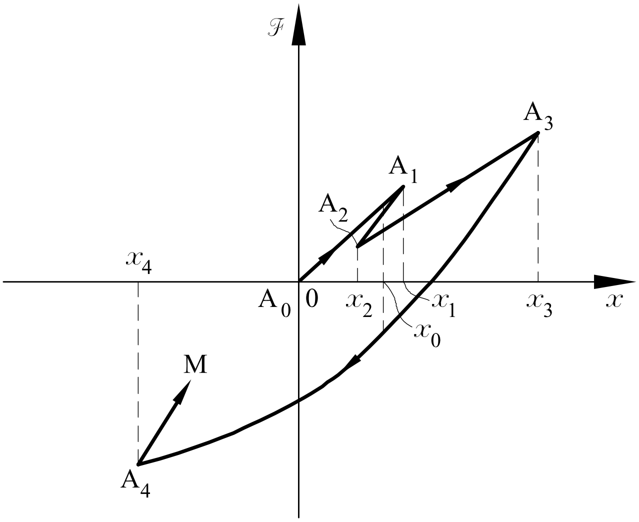

Figure A.1: Graph force versus displacement for a hysteresis function.

Assumption 1 is what, in the current literature, is called the *rate-independent property* [446]. To precise the form of the functional $\mathcal{F}$, [51] elaborates on previous works to propose the following form:

$$\frac{d\mathcal{F}}{dt} = g\left(x, \mathcal{F}, \operatorname{sign}\left(\frac{dx}{dt}\right)\right)\frac{dx}{dt}\,. \tag{A.1}$$

Consider the equation

$$\frac{d^2x}{dt^2} + \mathcal{F}(t) = p(t) \tag{A.2}$$

for some given input $p(t)$ and initial conditions

$$\frac{dx}{dt}(t_0), \quad x(t_0) \quad \text{and} \quad \mathcal{F}(t_0) \tag{A.3}$$

at the initial time instant t_0. Equations (A.1) and (A.2) describe completely a hysteretic oscillator.

The paper [51] notes that it is difficult to give explicitly the solution of equation (A.1) due to the nonlinearity of the function g. For this reason, the author proposes the use of a variant of the Stieltjes integral to define the functional $\mathcal{F}$:

$$\mathcal{F}(t) = \mu^2 x(t) + \int_{\beta}^{t} F\left(V_s^t\right) dx(s)\,, \tag{A.4}$$

where $\beta \in [-\infty, +\infty)$ is the time instant after which the displacement and force are defined. The term V_s^t is the total variation of x in the time interval $[s, t]$. The function F is chosen in such a way that it satisfies some mathematical properties compatible with the hysteresis property. The following is an example of this choice given in [51] so that these mathematical properties are satisfied:

$$F(u) = \sum_{i=1}^{N} A_i e^{-\alpha_i u}, \qquad \text{with} \quad \alpha_i > 0 \tag{A.5}$$

Equations (A.2)-(A.5) can then be written in the form

$$\frac{d^2x}{dt^2} + \mu^2 x + \sum_{i=1}^{N} Z_i = p(t) \tag{A.6}$$

$$\frac{dZ_i}{dt} + \alpha_i \left|\frac{dx}{dt}\right| Z_i - A_i\frac{dx}{dt} = 0; \qquad i = 1, \ldots, N \tag{A.7}$$

Equations (A.6)-(A.7) are what is now known as the Bouc model. The derivation of these equations is detailed in [51]. The objective here is not to enter in these details, but only give a short idea on the origin of the model.

Equation (A.7) has been extended in [455] to describe restoring forces with hysteresis in the following form:

$$\dot{z} = -\alpha|\dot{x}|z^n - \beta\dot{x}|z^n| + A\dot{x}, \quad \text{for} \quad n \text{ odd}, \tag{A.8}$$

$$\dot{z} = -\alpha|\dot{x}|z^{n-1}|z| - \beta\dot{x}z^n + A\dot{x} \quad \text{for} \quad n \text{ even.} \tag{A.9}$$

Equations (A.8)-(A.9) constitute the earliest version of what is called now the Bouc-Wen model. This chapter presents an overview of the literature related to this model. It can be seen in Figure A.2 that the last few years have witnessed an increasing interest to this model with a book dedicated exclusively to the Bouc-Wen model [203]. This literature encompasses a wide range of issues ranging from identification to modeling, control, analysis, etc. These issues are treated in detail in the following sections.

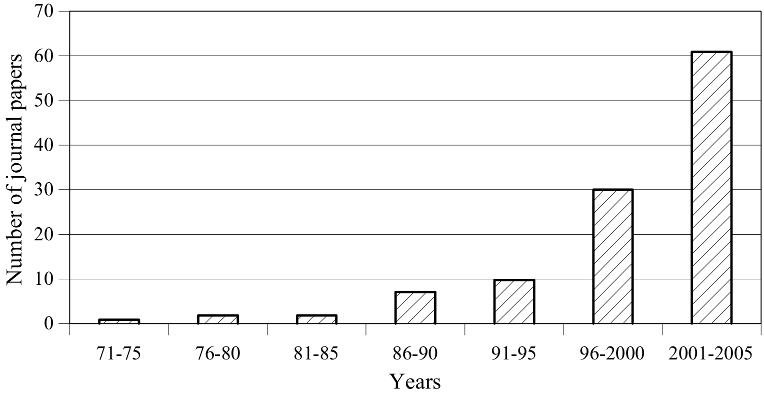

Figure A.2: Evolution of the Bouc-Wen model literature.

A.2 Physical and mathematical consistency of the model

In the current literature, the Bouc-Wen model is mostly used within the following black-box approach: given a set of experimental input-output data, how to adjust the Bouc-Wen model parameters so that the output of the model matches the experimental data? The use of system identification techniques is one practical way to perform this task. Once an identification method has been applied to tune the Bouc-Wen model parameters, the resulting model is considered as a "good" approximation of the true hysteresis when the error between the experimental data and the output of the model is small enough. Then this model is used to study the behavior of the true hysteresis under different excitations.

By doing this, it is important to consider the following remark. It may happen that a Bouc-Wen model presents a good matching with the experimental real data for a specific input, but does not necessarily keep significant physical properties which are inherent to the real data, independently of the exciting input. In this section we draw the attention to this issue by considering physical properties like stability, passivity, thermodynamic consistency etc.

On the other hand, the Bouc-Wen model is a nonlinear differential equation, and has to have some general mathematic properties to be used properly. We consider in this section the existence and uniqueness of the solution of the model, along with the bijective relationship between the parameters and the input/output behavior.

A.2.1 Physical consistency of the Bouc-Wen model

The following properties have been considered in the literature:

- Bounded input-bounded output (BIBO) stability
- Consistency with the asymptotic motion of physical systems
- Passivity
- Thermodynamic admissibility
- Accordance with Drucker and Il'iushin stability postulates
- Consistency with the hysteresis property

BIBO stability

The BIBO stability property of the Bouc-Wen model has been formulated in [199] as follows: Let us conceptualize a nonlinear hysteretic behavior as a map $x(t) \mapsto \Phi_s(x)(t)$, where x represents the time history of an input variable and $\Phi_s(x)$ describes the time history of the hysteretic output variable. For any bounded input x, the output of the true hysteresis $\Phi_s(x)$ is bounded. This bounded BIBO stability property stems from the fact that we are dealing with mechanical and structural systems that are stable in open loop.

The Bouc-Wen model that approximates the true hysteresis $\Phi_s(x)$ is

$$\Phi_{BW}(x)(t) = \alpha k x(t) + (1-\alpha) D k z(t), \tag{A.10}$$

$$\dot{z} = D^{-1}\left(A\dot{x} - \beta|\dot{x}|\,|z|^{n-1}z - \gamma\dot{x}|z|^{n}\right) \tag{A.11}$$

where $\dot{z}$ denotes the time derivative, $n > 1$, $D > 0$, $k > 0$, $0 < \alpha < 1$ and $\beta + \gamma \neq 0$ (the limit cases $n = 1$, $\alpha = 0$, $\alpha = 1$, $\beta + \gamma = 0$ are treated separately in [199]).

This model is BIBO stable if and only if the following set Ω of initial conditions $z(0)$ is nonempty:

$$\begin{aligned}\Omega = \{z(0) \in \mathbb{R} \text{ such that } \Phi_{BW} \text{ is BIBO stable for all } C^1 \\ \text{input signal } x(t) \text{ with fixed values of the parameters} \\ A, \beta, \gamma, n\}\end{aligned} \tag{A.12}$$

The following is proved in [199].

Theorem 1 *Let $x(t)$, $t \in [0, \infty)$ be a C^1 input signal and*

$$z_0 \triangleq \sqrt[n]{\frac{A}{\beta+\gamma}} \text{ and } z_1 \triangleq \sqrt[n]{\frac{A}{\gamma-\beta}} \tag{A.13}$$

Then, Table A.1 holds.

Case		Ω	Upper Bound on $\lvert z(t)\rvert$	Class
$A > 0$	$\beta+\gamma > 0$ and $\beta-\gamma \geq 0$	$\mathbb{R}$	$\max(\lvert z(0)\rvert, z_0)$	I
	$\beta-\gamma < 0$ and $\beta \geq 0$	$[-z_1, z_1]$	$\max(\lvert z(0)\rvert, z_0)$	II
$A < 0$	$\beta-\gamma > 0$ and $\beta+\gamma \geq 0$	$\mathbb{R}$	$\max(\lvert z(0)\rvert, z_0)$	III
	$\beta+\gamma < 0$ and $\beta \geq 0$	$[-z_0, z_0]$	$\max(\lvert z(0)\rvert, z_0)$	IV
$A = 0$	$\beta+\gamma > 0$ and $\beta-\gamma \geq 0$	$\mathbb{R}$	$\lvert z(0)\rvert$	V
	All Other Classes	$\varnothing$		

Table A.1: Classification of BIBO stable Bouc-Wen models.

It is shown in [199] that class V corresponds to a linear behavior so that it is irrelevant for the modeling of hysteresis behavior.

Consistency with the asymptotic motion of physical systems

Reference [199] considers a structural base-isolation device modeled as a SDOF system with mass $m > 0$ and viscous damping $c > 0$ plus a restoring force Φ characterizing the hysteretic behavior of the hysteretic material. The free motion of the system is described by the second order differential equation

$$m\ddot{x} + c\dot{x} + \Phi(x)(t) = 0 \tag{A.14}$$

with initial conditions $x(0)$ and $\dot{x}(0)$, and the restoring force is assumed to be described by the Bouc-Wen model (A.10)-(A.11). The following is proved in [199].

Theorem 2 *For every initial conditions* $x(0) \in \mathbb{R}$, $\dot{x}(0) \in \mathbb{R}$ *and* $z(0) \in \Omega \neq \varnothing$, *the following holds:*

a) For all classes I–IV in Table A.1, the signals $x(t)$, $\dot{x}(t)$ *and* $z(t)$ *are bounded and* C^1.

b) Assume that the Bouc-Wen model belongs to the classes I or II, then there exist constants x_∞ *and* z_∞ *which depend on the Bouc-Wen model parameters* $(\alpha, D, k, A, \beta, \gamma, n)$, *the system parameters* (m, c) *and the initial conditions* ($x(0)$, $\dot{x}(0)$ *and* $z(0)$), *and there exists a constant* $\bar{c}$ *that depends on the parameters* $m, k, A, \alpha, \beta, \gamma$ *such that for all* $c \geq \bar{c}$, *we have:*

$$\lim_{t\to\infty} x(t) = x_\infty \tag{A.15}$$

$$\lim_{t\to\infty} z(t) = z_\infty \tag{A.16}$$

$$\alpha x_\infty + (1-\alpha) D z_\infty = 0 \tag{A.17}$$

Furthermore, we have:

$$\dot{x} \in L_1\big([0,\infty)\big) \text{ and } \lim_{t\to\infty} \dot{x}(t) = 0 \tag{A.18}$$

Accordingly, Theorem 2 shows that, for the classes I and II, the displacement x goes to a constant value asymptotically and that the velocity $\dot{x}$ goes to zero. This is compatible with experimental observations for base-isolation devices which means that both classes are good candidates for the description of the real physical behavior of a base-isolation system. Based on numerical simulations, classes III and IV are shown not to behave in accordance with experimental observations.

Passivity

Passivity is related to the energy dissipation and means that the system does not generate energy. In [199], the model (A.10)-(A.11) is written as:

$$\begin{aligned}
\dot{x} &= u \\
\dot{z} &= D^{-1}\left(Au - \beta|u||z|^{n-1}z - \gamma u|z|^n\right) \\
y &= \alpha k x + (1-\alpha) D k z
\end{aligned} \tag{A.19}$$

where u is the input of the model and y is its output. Denoting

$$l_1 = \frac{(1-\alpha)D^2 k}{2A} > 0 \tag{A.20}$$

$$l_2 = \frac{\alpha k}{2} > 0 \tag{A.21}$$

$$W(x,z) = l_1 z^2 + l_2 z^2 \tag{A.22}$$

it is shown that the Bouc-Wen model is passive with respect to the storage function W.

Thermodynamic admissibility

The thermodynamic admissibility is investigated in [141] using the endochronic theory (a theory of viscoplasticity without a yield surface, proposed in [438]). The Bouc-Wen type models that are considered are univariate and tensorial. The Bouc model [51] is univariate and is defined as

$$w(t) = A_0 u(t) + z(t) \tag{A.23}$$

$$z(t) = \int_0^{\vartheta(t)} \mu\big(\vartheta(t) - \vartheta'\big) \frac{du}{d\vartheta'}\, d\vartheta' \tag{A.24}$$

where $\mu = \mu(\vartheta(t))$ is the hereditary kernel and $A_0 \geq 0$. The input u is a relative displacement between two structural elements, while the output w is a structural restoring force. The time function ϑ is positive and non-decreasing which directly depends on the strain and/or the stress tensors, and it is named internal or intrinsic time. One of the definitions of ϑ proposed by Bouc is the total variation of u:

$$\vartheta(t) = \int_0^t \left| \frac{du}{d\tau} \right| d\tau, \quad \text{or, equivalently,} \quad d\vartheta = |du|, \quad \text{with} \quad \vartheta(0) = 0 \tag{A.25}$$

In this case equation (A.24) becomes

$$dz = Adu - \beta z|du| \tag{A.26}$$

A more general formulation of (A.26) was also proposed in [50]:

$$dz = A\, du - \beta z|du| - \gamma|z|du \quad \text{with} \quad \gamma < \beta \tag{A.27}$$

while [455] suggested a further modification, introducing the positive exponent n:

$$dz = A\, du - (\beta \text{ sign } (z\, du) + \gamma)\, |z|^n\, du \tag{A.28}$$

Reference [28] introduced the stiffness and strength degradation effects in the Bouc–Wen model (A.28). Only the strength degradation case is considered in [141]:

$$dz = A\, du - \nu\, (\beta \text{ sign } (z\, du) + \gamma)\, |z|^n\, du \tag{A.29}$$

where ν is a positive and increasing function of the energy dissipated by the system. A tensorial generalization of (A.28) is given in [236] for isotropic materials with elastic hydrostatic behavior:

$$\sigma_d = A_0 \varepsilon_d + \mathbf{z}, \tag{A.30}$$

$$d\mathbf{z} = A\, d\varepsilon_d - \beta \mathbf{z}||\mathbf{z}||^{n-2}|\mathbf{z} : d\varepsilon_d| - \gamma \mathbf{z}||\mathbf{z}||^{n-2}(\mathbf{z} : d\varepsilon_d) \tag{A.31}$$

where ε_d and σ_d are the deviatoric part of the small strain tensor and of the Cauchy stress tensor, respectively; $\mathbf{z}$ is the tensor defining the hysteretic part of the stress, while $||\cdot||$ is the standard L_2-norm.

The following has been proved in [141].

Theorem 3 *The Bouc-Wen models of equations* (A.23)–(A.31) *fulfill the second principle of Thermodynamics if and only if the following holds:*

$$n > 0 \tag{A.32}$$

$$\beta > 0 \tag{A.33}$$

$$-\beta \leq \gamma \leq \beta \tag{A.34}$$

Accordance with Drucker and Il'iushin stability postulates

Drucker's postulate [38] implies that the hysteresis system should not produce a negative energy dissipation when the unloading-reloading process occurs without load reversal. For the Bouc-Wen model, it has been noted in many references that this may not be the case, although the effect of this violation on the expected results may be minor [66], [424], [458], [184], [382].

An attempt to reduce the violation is presented in [65] by modifying the Bouc-Wen model. On the other hand, [67], [68] show that for $n = 1$, $\beta + \gamma > 0$ and $\gamma - \beta \leq 0$ (β being positive by assumption), the Bouc-Wen model verifies Drucker's postulate. The more general result for n arbitrary is obtained in Theorem 3 of [141], as the thermodynamic consistency for the Bouc-Wen model implies that it verifies
Drucker's postulate.

Consistency with the hysteresis property

It is shown in [201, 194] that, to be consistent with the hysteresis property, the Bouc-Wen model (A.10)-(A.11) has to verify

$$\max_{t \geq 0} (x(t)) \leq \frac{(1-\alpha) D z_0}{\alpha} \tag{A.35}$$

where $\max(x(t))$ is the maximal value of the input $x(t)$ for $t \geq 0$. The hysteresis property means that the output depends on the sign of the derivative of the input.

Conclusion

As a conclusion of the above results, for univariate Bouc-Wen models, the class I of Table A.1 is BIBO stable, consistent with the motion of physical systems, passive, and consistent with the second law of Thermodynamics. Furthermore, condition (A.35) is needed for the consistency with the hysteresis property. For the multivariate Bouc-Wen model, the only consistency result available in the literature is that of [141] stated in Theorem 3.

A.2.2 Mathematical consistency of the Bouc-Wen model

This section presents the results available in the literature with regard to

1. The existence and uniqueness of the solution of the Bouc-Wen model.
2. The uniqueness of the description of the Bouc-Wen model.

Existence and uniqueness of solutions

It is shown in [199] that the differential equation (A.10)-(A.11) has a unique solution if $n \geq 1$.

Uniqueness of the description

It is shown in [200] that there exists an infinite number of different sets of Bouc-Wen model parameters that lead to the same input/output behavior of the model. This means that some parameters of the model are redundant. To eliminate this redundancy, a normalized form of the Bouc-Wen model is introduced in [201, 194] by using the transformation

$$w(t) = \frac{z(t)}{z_0} \tag{A.36}$$

so that the model (A.10)-(A.11) can be written in the form

$$\begin{aligned} \Phi_{BW}(x)(t) &= \kappa_x x(t) + \kappa_w w(t) && \text{(A.37)} \\ \dot{w}(t) &= \rho \left(\dot{x} - \sigma |\dot{x}(t)| \, |w(t)|^{n-1} w(t) + (\sigma - 1) \dot{x}(t) |w(t)|^n \right) && \text{(A.38)} \end{aligned}$$

where

$$\begin{aligned} \rho &= \frac{A}{D z_0} > 0, \\ \sigma &= \frac{\beta}{\beta + \gamma} \geq \frac{1}{2}, \\ \kappa_x &= \alpha k > 0, \\ \kappa_w &= (1 - \alpha) D k z_0 > 0. \end{aligned} \tag{A.39}$$

This form is defined only for the class I as it is consistent with the physical properties considered before. The following inequality is also obtained: $\max_{t \geq 0} w(t) = \max\left(|w(0)|, 1\right)$.

Conclusion

The mathematical and physical consistency conditions show that the Bouc-Wen model has to be used under the normalized form (A.37)-(A.38), along with the inequalities $n \geq 1$, $\rho > 0$, $\sigma \geq 1/2$, $\kappa_x > 0$, $\kappa_w > 0$ and $\max_{t \geq 0}(x(t)) \leq \dfrac{\kappa_w}{\kappa_x}$. In this case, we also have $\max_{t \geq 0} w(t) = \max(|w(0)|, 1)$.

A.3 Description of the hysteresis loop

When the input displacement is periodic with a loading-unloading shape, it is observed by means of numerical simulations that the output Bouc-Wen restoring force is also periodic asymptotically with the same period as the input. This fact has been demonstrated analytically only recently due to the nonlinearity of the model [200]. The hysteresis loop is the cycle obtained asymptotically when the hysteresis output is plotted versus the displacement input. Two types of problems have been discussed in the literature:

- Consider that the input is a periodic displacement and the output is the Bouc-Wen restoring force.
- Consider that the input is an external periodic force, and the output is the displacement of a second-order system that includes a Bouc-Wen hysteresis.

For the first case, the periodic input displacement signal with a loading-unloading shape is defined formally in [200]: $x(t)$ is continuous over the time interval $[0, \infty)$ and is periodic with a period $T > 0$. Furthermore, there exists a scalar T^+ with $0 < T^+ < T$ such that $x(t)$ is a C^1 increasing function of time on the interval $(0, T^+)$ and a C^1 decreasing function of time on the interval (T^+, T). The quantities $X_{\min} = x(0)$ and $X_{\max} = x(T^+) > X_{\min}$ denote the minimal and the maximal values of the input signal, respectively. The signal $x(t)$ is called wave T-periodic and it is illustrated in Figure A.3.

The description of the hysteresis loop uses the following instrumental functions:

$$\varphi^-_{\sigma,n}(\mu) = \int_0^\mu \frac{du}{1 + \sigma|u|^{n-1}u + (\sigma - 1)|u|^n} \tag{A.40}$$

is well defined, C^∞ and strictly increasing on $(-1, 1]$, so that it is invertible, with inverse $\psi^-_{\sigma,n}$.

$$\varphi^+_{\sigma,n}(\mu) = \int_0^\mu \frac{du}{1 - \sigma|u|^{n-1}u + (\sigma - 1)|u|^n} \tag{A.41}$$

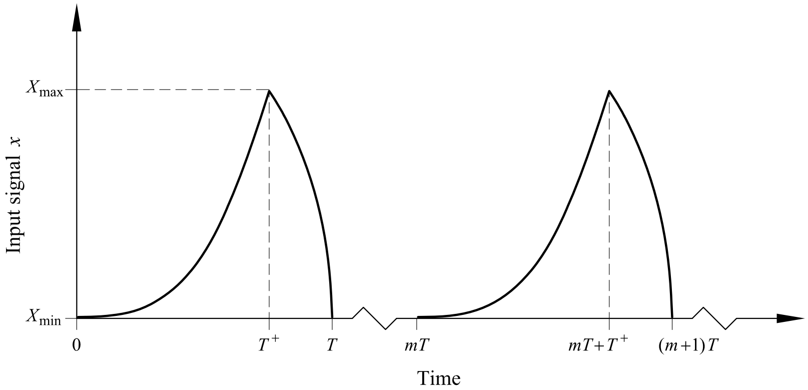

Figure A.3: The T-periodic input signals.

is well defined, C^∞ and strictly increasing on $[-1, 1)$, so that it is invertible, with inverse $\psi^+_{\sigma,n}$.

$$\varphi_{\sigma,n}(\mu) = \varphi^-_{\sigma,n}(\mu) + \varphi_{\sigma,n}(\mu)^+ \tag{A.42}$$

is well defined, C^∞ and strictly increasing on $(-1, 1)$, so that it is invertible with inverse $\psi_{\sigma,n}$.

The analytical description of the hysteresis loop is given in the following.

Theorem 4 *Define the functions ω_m and ϕ_m for any nonnegative integer m as*

$$\omega_m(\tau) = w(mT + \tau) \text{ for } \tau \in [0, T] \tag{A.43}$$

$$\phi_m(\tau) = \kappa_x x(\tau) + \kappa_w \omega_m(\tau) \text{ for } \tau \in [0, T] \tag{A.44}$$

Then, the sequence of functions $\{\phi_m\}_{m\geq 0}$ (resp. $\{\omega_m\}_{m\geq 0}$) converges uniformly on the interval $[0, T]$ to a continuous function $\bar{\Phi}_{BW}$ (resp. $\bar{w}$) defined as:

$$\bar{\Phi}_{BW}(\tau) = \kappa_x x(\tau) + \kappa_w \bar{w}(\tau) \text{ for } \tau \in [0, T] \tag{A.45}$$

$$\bar{w}(\tau) = \psi^+_{\sigma,n}\left(\varphi^+_{\sigma,n}\left[-\psi_{\sigma,n}(\rho(X_{\max} - X_{\min}))\right] + \rho(x(\tau) - X_{\min})\right) \quad \text{for} \quad \tau \in [0, T^+] \tag{A.46}$$

$$\bar{w}(\tau) = -\psi^+_{\sigma,n}\left(\varphi^+_{\sigma,n}\left[-\psi_{\sigma,n}(\rho(X_{\max} - X_{\min}))\right] - \rho(x(\tau) - X_{\max})\right) \quad \text{for} \quad \tau \in [T^+, T] \tag{A.47}$$

Define the time function $\bar{\phi}_{BW}$ as $\bar{\phi}_{BW}(t) = \bar{\Phi}_{BW}(\tau)$ where the time $t \in [0, \infty)$ is written as $t = mT + \tau$ for all integers $m = 0, 1, 2, \dots$ and all real numbers $0 \leq \tau < T$. Theorem 4 means that the time function hysteretic output $\Phi_{BW}(x)(t)$ of the Bouc-Wen model approaches asymptotically the T-periodic function $\bar{\phi}_{BW}(t)$. The limit cycle is the graph $(x(\tau)\ ,\ \bar{\Phi}_{BW}(\tau))$ parameterized by the variable $0 \leq \tau \leq T$. Equations (A.45) and (A.46) correspond to the loading, that is to an increasing input $x(\tau)$ with $0 \leq \tau \leq T^+$, while (A.45) and (A.47) correspond to the unloading, that is to a decreasing input $x(\tau)$ with $T^+ \leq \tau \leq T$.

In [342] it is assumed that the exponent $n = 1$. The hysteretic part of system is then governed by

$$\dot{z} = A\dot{x} - \left(\bar{\beta}|\dot{x}|z + \bar{\gamma}\dot{x}|z|\right). \tag{A.48}$$

The input signal $x(t)$ is assumed wave T-periodic and the output is also assumed asymptotically wave T-periodic. Depending on the signs of velocity $\dot{x}$ and hysteretic restoring force z, the hysteretic loop is divided into four regions. In each region, equation (A.48) is integrated leading to

$$z = \begin{cases} -\dfrac{A - B_1\, e^{(\bar{\beta}-\bar{\gamma})x}}{\bar{\beta}-\bar{\gamma}} & (\bar{\beta}-\bar{\gamma} \neq 0), \\ Ax + D_1 & (\bar{\beta}-\bar{\gamma} = 0), \end{cases} \qquad \text{for } \dot{x} \leq 0, \quad z \geq 0, \tag{A.49}$$

$$z = \begin{cases} -\dfrac{A - B_2\, e^{(\bar{\beta}+\bar{\gamma})x}}{\bar{\beta}+\bar{\gamma}} & (\bar{\beta}+\bar{\gamma} \neq 0), \\ Ax + D_2 & (\bar{\beta}+\bar{\gamma} = 0), \end{cases} \qquad \text{for } \dot{x} \leq 0, \quad z \leq 0, \tag{A.50}$$

$$z = \begin{cases} \dfrac{A - B_3\, e^{-(\bar{\beta}-\bar{\gamma})x}}{\bar{\beta}-\bar{\gamma}} & (\bar{\beta}-\bar{\gamma} \neq 0), \\ Ax + D_3 & (\bar{\beta}-\bar{\gamma} = 0), \end{cases} \qquad \text{for } \dot{x} \geq 0, \quad z \leq 0, \tag{A.51}$$

$$z = \begin{cases} \dfrac{A - B_4\, e^{-(\bar{\beta}+\bar{\gamma})x}}{\bar{\beta}+\bar{\gamma}} & (\bar{\beta}+\bar{\gamma} \neq 0), \\ Ax + D_4 & (\bar{\beta}+\bar{\gamma} = 0), \end{cases} \qquad \text{for } \dot{x} \geq 0, \quad z \geq 0, \tag{A.52}$$

where B_i and D_i are integration constants. To obtain the values of these constants, it is assumed that the hysteresis loop is continuous, and the continuity condition leads to four equations for the integration constants. Due to the nonlinearity of the equations, these constants are not determined exactly. Instead, it is assumed that $\bar{\beta} = \varepsilon\beta$ and $\bar{\gamma} = \varepsilon\gamma$ where ε is a small positive constant. An expansion in power series of ε allows to obtain an approximate description of the hysteresis loop by neglecting the ε^3 and higher powers.

In [124] equation (A.11) is integrated for $D = 1$ and $n = 2$. It is claimed that

$$z = \frac{\sqrt{AB}}{B} \tan\left(\sqrt{AB}(x+c)\right) \qquad \text{for } B < 0, \tag{A.53}$$

$$z = \frac{\sqrt{AB}}{B} \tanh\left(\sqrt{AB}(x+c)\right) \qquad \text{for } B > 0, \tag{A.54}$$

where B is the coefficient that multiplies z in equation (A.11) and c an integration constant (the expression of c is not given analytically and is supposed to be determined from experiments). This description is incorrect as $\sqrt{AB}$ cannot be a real number in equation (A.53) since $A > 0$ and $B < 0$.

In [387], equivalent linearization is used to approximate the system response under sinusoidal base excitation. The system is described by

$$m\ddot{x}_r + kx_r + f(x_r, \dot{x}_r) = -m\ddot{y} \tag{A.55}$$

$$f(x_r, \dot{x}_r) = k_d x_r + c_d \dot{x}_r + \alpha z \tag{A.56}$$

$$\dot{z} = A\dot{x}_r - \gamma|\dot{x}_r z^{n-1}|z - \beta\dot{x}_r|z|^n \tag{A.57}$$

where x_r is the relative displacement and $y = y_0 \cos(\omega t)$. Equivalent linearization assumes that equations (A.55)-(A.57) are equivalent to the single equation

$$\ddot{x}_r + 2\xi\omega_{ne}\dot{x}_r + \omega_{ne}^2 k x_r = -\ddot{y}, \tag{A.58}$$

where ξ and ω_{ne} are the equivalent system parameters and are determined as a function of the frequency ω. This method assumes that the solution of equations (A.55)-(A.57) is a sine wave. Its phase and amplitude are given as a function of the equivalent parameters. Two main disadvantages of this method are that (1) it is not applicable when the input signal y is not a sine wave and (2) no formal upper bound on the error between the approximated solution and the exact one is obtained. The size of the error is checked by means of experiments.

Also in [387], an averaging method is used to approximate the response to a harmonic excitation. This method assumes a sine wave steady-state solution for the variables x_r and z, the amplitude a and phase ϕ of which is considered time-varying. There is a mistake in [387, eq(35)-(37)] where (35) is obtained assuming a and ϕ constant, while they are time-varying in (37).

A.4 Variation of the hysteresis loop with the model parameters

Due to the nonlinearity of the Bouc-Wen model, most studies on the influence of the model parameters on the hysteresis loop shape have been based on numerical simulations. This is the subject of Section A.4.2. The analytical description of the hysteresis loop in [200] allowed a systematic analysis of the Bouc-Wen hysteresis cycle in [195]. This is the subject of Section A.4.1.

A.4.1 Analytical study of the influence of the model parameters on the hysteresis loop

In [195], it is considered that the input displacement signal $x(t)$ is wave T-periodic with $X_{\min} = -X_{\max}$. This allows to define a normalized input

$$\bar{x}(t) = \frac{x(t)}{X_{\max}} \tag{A.59}$$

The hysteresis part of the limit cycle is derived for loading as

$$\bar{w}(\bar{x}) = \psi^{+}_{\sigma,n}\left[\varphi^{+}_{\sigma,n}(-\psi_{\sigma,n}(\delta)) + \frac{\delta}{2}(\bar{x}+1)\right], \tag{A.60}$$

where $\delta = 2\rho X_{\max}$. Unloading is not considered in [195] as it is shown that loading and unloading are symmetric.

To analyze the influence of the normalized set of parameters (σ, δ and n) on the shape of the limit cycle defined by the graph $(\bar{x}, \bar{w}(\bar{x}))$, [195] considers three optics:

1. Analyzing the variation of $\bar{w}(\bar{x})$ as a function of each parameter (σ, δ and n) separately. This corresponds to studying the variation of the point Q along the $\bar{w}$-axis in Figure A.4.
2. Studying the variation of the the point S along the $\bar{x}$-axis in Figure A.4 (that is the width of the hysteresis loop).
3. Defining four regions of the graph $(\bar{x}, \bar{w}(\bar{x}))$ and studying the evolution of the points defining each region. These regions are:
   (a) linear region $R_l = [P_{sl}, P_{lt}]$,
   (b) plastic region $R_p = [P_{tp}, P_p]$,
   (c) transition region $R_t = [P_{lt}, P_{tp}]$,
   (d) transition region $R_s = [P_s, P_{sl}]$.

The obtained results are summarized in tables where only the results obtained analytically are reported. The maximal value of the hysteretic output is shown to be $\psi_{\sigma,n}(\delta)$. The variation of this term with respect to each of the

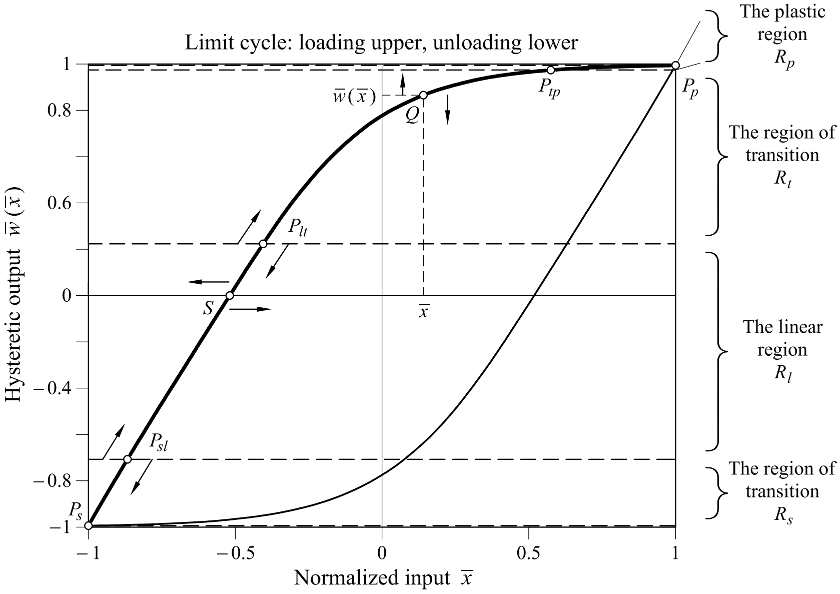

Figure A.4: Methodologies of the analysis of the variation of $\bar{w}(\bar{x})$.

three parameters σ, δ and n is given in Table A.2. For example, the second row of the table is to be read as follows: the first column says that the term $\psi_{\sigma,n}(\delta)$ is analyzed with respect to the parameter σ. The second column says that the term $\psi_{\sigma,n}(\delta)$ is increasing ($\uparrow$) from the value $\psi_{\frac{1}{2},n}(\delta)$ that corresponds to $\sigma = \frac{1}{2}$ to the value $\psi_n^+(\delta)$ that corresponds to $\sigma = +\infty$.

Table A.3 summarizes the results of the variation of the zero of the hysteretic output with respect to the model parameters, δ, σ and n. The variation of the hysteretic output with the Bou-Wen normalized model parameters is given in Table A.4.

A detailed analytical study of the four regions of the Bouc-Wen model hysteresis loop is also presented in [195].

A.4.2 Study of the variation of the hysteresis loop with the Bouc-Wen model parameters by means of numerical simulations

As explained in Section A.3, [387] assumes a harmonic approximation of the periodic response of a second-order system coupled with a Bouc-Wen hysteresis. Based on this approximation, and using numerical simulations, the conclusions of the study are the following:

$\psi_{\sigma,n}(\delta)$	0	$\uparrow$	1
δ	0		$+\infty$
$\psi_{\sigma,n}(\delta)$	$\psi_{\frac{1}{2},n}(\delta)$	$\uparrow$	$\psi_n^+(\delta)$
σ	$\frac{1}{2}$		$+\infty$
$\psi_{\sigma,n}(\delta)$	$\psi_{\sigma,1}(\delta)$	$\uparrow$	$\begin{cases} \frac{\delta}{2} & \text{if} \quad \delta \in (0,2] \\ 1 & \text{if} \quad \delta > 2 \end{cases}$
n with $\sigma \leq 1$	1		$+\infty$
$\psi_{\sigma,n}(\delta)$	$\psi_{\sigma,1}(\delta)$		$\begin{cases} \frac{\delta}{2} & \text{if} \quad \delta \in (0,2] \\ 1 & \text{if} \quad \delta > 2 \end{cases}$
n with $\sigma > 1$	1		$+\infty$

Table A.2: Variation of the maximal hysteretic output with the normalized Bouc-Wen model parameters.

$\bar{x}^{\circ}$	0	$\downarrow$	-1
δ	0		$+\infty$
$\bar{x}^{\circ}$	$\frac{2}{\delta}\psi_{\frac{1}{2},n}(\delta) - 1$	$\downarrow$	-1
σ	$\frac{1}{2}$		$+\infty$
$\bar{x}^{\circ}$	$\frac{2}{\delta}\varphi_{\sigma,1}^{-}(\psi_{\sigma,1}(\delta)) - 1$	$\uparrow$	$\begin{cases} 0 & \text{if} \quad \delta \in (0,2] \\ \frac{2}{\delta} - 1 & \text{if} \quad \delta > 2 \end{cases}$
n	1		$+\infty$

Table A.3: Variation of the hysteretic zero $\bar{x}^{\circ}$ with the normalized Bouc-Wen model parameters.

1. When the amplitude of the excitation is small, the frequency response of the system is quasilinear hysteretic system, while the system exhibits a large multivalued frequency regions as the amplitude of the excitation increases.

2. As the parameter γ varies from negative value to positive one, the system frequency response curves gradually vary from hardening character to a quasilinear character and then to soft character.

3. When β is increased, the response amplitude is decreased.

4. When A is increased, the system natural frequency is increased.

5. When α is increased, the damping force is increased, the hysteresis force loop will become slim and the damping force will be more similar to

viscous damping force, in addition, large α will make the system more like linear system.

The study in [463] reports that there are five kinds of hysteresis loops with physical meaning depending on the respective signs of the quantities $\beta+\gamma$ and $\beta-\gamma$. Hardening and softening behaviors are shown to be related to the sign of $\beta+\gamma$. It is also noted that the parameter A controls the slope of the hysteresis loop at $z=0$. Using numerical simulations it is shown that the parameter n governs the smoothness of the transition from linear to nonlinear range. It is also observed that an increase of the parameter A increases the resonant frequency and reduces the resonant peak. Moreover, it is observed that the increase of the parameters A and n makes the hysteresis loop narrower.

A.5 Interpretation of the model parameters

In this section, the interpretation of the standard and normalized parameters of the Bouc-Wen model is discussed.

A.5.1 Interpretation of the standard Bouc-Wen model parameters

The parameters α, A, β, γ and n play the role of governing and controlling the scale and general shape of the hysteresis loop. Due to the lack of an analytical expression of the hysteresis loop, most works addressing this issue have used numerical simulation to understand the influence of these parameters [65, 387, 463, 280, 299, 342]. The way these simulations have been done is by fixing four parameters and varying one (the free parameter). As shown in Section A.4.1, this methodology is hampered by the following facts:

1. The variation of the hysteresis loop with the free parameter depends on the precise values of the fixed parameters.
2. Any given quantity related to the hysteresis loop (like maximum value, width, etc) does not depend on a single parameter but rather on the whole set of parameters.

As a consequence, most of the results obtained in the literature are either incomplete or incorrect. A more analytic approach is given in [195] using the normalized parameters and its results are given in the following section.

A.5.2 Interpretation of the normalized Bouc-Wen model parameters

The parameters of the normalized form of the model are interpreted as follows. ρ is the slope of the linear zone for $X_{\max} = 1$, or the inverse of the apparent yield point of the nonlinear component of the Bouc-Wen model. The Parameter δ can be seen as a measure for the ductility of the model, while the parameter σ distinguishes the softening or the hardening behaviors of the hysteretic component and therefore the consistency with the laws of Thermodynamics. The parameter n characterizes the transition from linear to plastic behavior along the axis of ordinates in the map $(\bar{x}, \bar{w}(\bar{x}))$.

A.6 The Bouc-Wen model parameter identification

Identifying the Bouc-Wen model parameters consists in proposing a signal input (or several signal inputs) and an identification algorithm that uses the measured output of the model along with that input to determine the unknown model parameters. This problem has stirred a lot of research effort due to its difficulty being nonlinear and non-differentiable. Some identification methods have been proposed with a rigorous analysis of the convergence of the parameters to their true values, while others relied on numerical simulations and experimentation. In the next, we give an overview of these methods.

A.6.1 Least-squares based identification

Reference [298] presents a three-stage identification algorithm that is a combination of sequential regression analysis, least-squares analysis and/or Gauss-Newton method along with the extended Kalman filtering technique.

In the first stage of identification, assuming equivalent linear system at each time interval and by using the sequential regression analysis, the system stiffness and damping are identified by means of the following recursive formulation:

$$\mathbf{a}_{k+1} = \mathbf{a}_k + \mathbf{P}_k \mathbf{H}_{k+1}^T (1 + \mathbf{H}_{k+1} \mathbf{P}_k \mathbf{H}_{k+1}^T)^{-1} \cdot (\mathbf{q}_{k+1} - \mathbf{H}_{k+1} \mathbf{a}) \tag{A.61}$$

where $\mathbf{q}_{k+1}$ = the actual $(k+1)$ measurement, $\mathbf{P}_k^{-1} = \mathbf{H}_k^T \mathbf{H}_k$ and $\mathbf{H}_{k+1} \mathbf{a}_k$ is the estimate of this measurement, while k = time step; N = degrees of freedom and $\mathbf{a} = [c_1, c_2, \ldots, c_N, k_1, k_2, \ldots, k_N]^T$.

In the second identification stage, a fixed $n = 1$ is assumed, and the model parameters (A, β, γ) are identified using the least-squares method proposed in

[419] for different α values and through minimizing the following error function:

$$E = \sum_{i=1}^{m} \left[\dot{z}_i - AI_{1i} + \beta I_{2i} + \gamma I_{3i}\right]^2 \tag{A.62}$$

where $I_{1i} = \dot{x}$, $I_{2i} = |\dot{x}||z_i|^{n-1} z_i$ and $I_{3i} = |\dot{x}||z_i|^n$.

In the third stage of identification, the extended Kalman filter technique is used to obtain better identification results by using the results from the second stage as an initial guess to the third stage to speed convergence.

Paper [264] describes an iterative least squares procedure based on a modified Gauss-Newton approach to perform the parameter identification of an extended version of the Bouc-Wen model that accounts for strength and stiffness degradation by [28].

References [80], [402] present an on-line identification method based on a least-squares adaptive law with the forgetting factor [206]. For an unknown mass m, a Bouc-Wen hysteresis element model with additional polynomial-type nonlinear terms, is used to investigate the effects of persistence of excitation and of under- and overparameterization. This model form is given as

$$z = m\ddot{x} + kx + c\dot{x} + dx^3 - \int_0^t (1/\eta)\left[\nu(\beta|\dot{x}||z|^{n-1}z - \gamma\dot{x}|z|^n)\right] \mathrm{d}\,t \tag{A.63}$$

where d is the cubic term parameter and c the linear damping parameter, while the stiffness parameter k replaces $(1/\eta)A$ in the common model degradation form. In this case, $\ddot{x}$ and z are supposed to be available to measurement while x and $\dot{x}$ are obtained by integration.

The filtered signals $\bar{z}$ in the identification process are given by

$$\bar{z} = \theta^{*T}\bar{\Phi} \tag{A.64}$$

where

$$\theta^* = [m, k, c, d, -(1/\eta)a_1\nu\beta, (1/\eta)a_1\nu\gamma, \, -(1/\eta)a_2\nu\beta, \ldots]^T \tag{A.65}$$

and

$$\bar{\Phi} = \left[\frac{s\ddot{x}}{(s+\alpha)}, \frac{sx}{(s+\alpha)}, \frac{s\dot{x}}{(s+\alpha)} \frac{sx^3}{(s+\alpha)}, \right. \\ \left. \frac{|\dot{x}||z|^0 z}{(s+\alpha)}, \frac{\dot{x}|z|}{(s+\alpha)} \frac{|\dot{x}||z|z}{(s+\alpha)}, \frac{|\dot{x}||z|^2}{(s+\alpha)}, \ldots\right]^T \tag{A.66}$$

To account for variable gain, a modified least-squares adaptive law with forgetting factor [206] is used.

Paper [287] presents an adaptive on-line identification methodology with a variable trace method to adjust the adaptation gain matrix.

In [299], a linear parameterized estimator is proposed for the on-line estimation of the hysteretic Bouc-Wen model with unknown coefficients (including the parameter n) written as

$$\dot{z} = A\dot{x} + \sum_{i=1}^{N} a_n \left[\beta|\dot{x}||z|^{i-1}z + \gamma\dot{x}|z|^{i}\right]. \tag{A.67}$$

where N is a known upper bound on n. A discrete-time form of (A.67) is defined as follows:

$$\begin{aligned} z(k) = z(k-1) &+ \Delta t A\dot{x}(k-1) \\ &+ \Delta t \sum_{i=1}^{N} a_i \big[\beta|\dot{x}(k-1)||z(k-1)|^{i-1}z(k-1) \\ &\qquad + \gamma\dot{x}(k-1)|z(k-1)|^{i}\big], \end{aligned} \tag{A.68}$$

where the coefficients a_i are 0 or 1. This discrete time model gives rise to the following discrete-time linearly parameterized estimator:

$$\begin{aligned} z(k) = z(k-1) &+ \theta_0(k)\dot{x}(k-1) \\ &+ \sum_{i=1}^{N} \big[\theta_{2i-1}(k)|\dot{x}(k-1)||z(k-1)|^{i-1}z(k-1) \\ &\qquad + \theta_{2i}(k)\dot{x}(k-1)|z(k-1)|^{i}\big], \end{aligned} \tag{A.69}$$

where the coefficients θ_i, $i = 0, \ldots, 2N$ are estimates at each time t_k of the corresponding coefficients shown in (A.68). Equation (A.69) indicates a linear parameterized form with respect to θ_i, $i = 0, \ldots, 2N$. Now set

$$\theta = [\theta_0, \theta_1, \theta_2, \ldots, \theta_{2N}]^T \tag{A.70}$$

where θ_i is a function of Δt and time-dependent model parameters. Also define

$$\begin{aligned} \phi(k-1) = \big[&\dot{x}(k-1)|\dot{x}(k-1)||z(k-1)|^0 z(k-1) \\ &\dot{x}(k-1)|z(k-1)|^1|\dot{x}(k-1)||z(k-1)|^1 z(k-1) \\ &\dot{x}(k-1)|z(k-1)|^2 \quad \ldots\ldots\ldots \quad |\dot{x}(k-1)| \\ &|z(k-1)|^{N-1}z(k-1)\dot{x}(k-1)|z(k-1)|^{N}\big] \end{aligned} \tag{A.71}$$

Then the restoring force at time t can be expressed as

$$z(k) = z(k-1) + \phi^T(k-1)\theta. \tag{A.72}$$

Based on the data collected from performance test, least-square method is used to estimate the model parameters, θ_i, $i = 0, \ldots, 2N$, for each discrete frequency where $N = 5$ was chosen.

In [389], the mechanical properties of low yield strength steel are studied to develop a new device for added damping, stiffness and seismic resistance of rhombic low yield strength steel plate. The Bouc-Wen model is used in the following form to approximate that mechanical behavior:

$$\dot{z} = A\dot{x} - \eta\big(\beta|\dot{x}||z|^{n-1} + \gamma\dot{x}|z|^n\big) \tag{A.73}$$

$$\eta = \left(\frac{\Delta_y}{\Delta_{y0}}\right)^{-n} \tag{A.74}$$

$$\Delta_y = \left(\frac{A}{\beta + \gamma}\right)^{1/n} \tag{A.75}$$

where Δ_y and Δ_{y0} are the present and the nominal yielding displacements, respectively.

A discrete form of (A.73) is rearranged as

$$\Delta z_i = Ay_{1i} - \beta y_{2i} - \gamma y_{3i}, \tag{A.76}$$

$$\text{where} \quad y_{1i} = \Delta x_i, \tag{A.77}$$

$$\text{and} \quad y_{2i} = \big(\beta\, \text{sign}\,(\dot{x}_i)|z_i|^{n-1} z_i\big)\Delta x_i, \tag{A.78}$$

$$\text{and} \quad y_{3i} = \big(\gamma |z_i|^n\big)\Delta x_i. \tag{A.79}$$

Then, the optimal coefficients of A, β and γ can be acquired by the fitting method of least squares through solving the following equation

$$\begin{bmatrix} \sum y_{1i}^2 & -\sum y_{1i}\, y_{2i} & -\sum y_{1i}\, y_{3i} \\ & \sum y_{2i}^2 & \sum y_{2i}\, y_{3i} \\ \text{sym.} & & \sum y_{3i}^2 \end{bmatrix} \begin{Bmatrix} A \\ \beta \\ \gamma \end{Bmatrix} = \begin{Bmatrix} \sum y_{1i}\, \Delta z_i \\ -\sum y_{2i}\, \Delta z_i \\ -\sum y_{3i}\, \Delta z_i \end{Bmatrix} \tag{A.80}$$

A.6.2 Kalman filter based identification

In [288] it is assumed that $n = 1$ and an extended Kalman filter is used to identify the rest of the parameters. A procedure for nonlinear system identification based on the extended Kalman filter is applied to soils under strong motion records [285]. The ground is modeled as 3DOFs hysteretic structure and the Bouc-Wen model is used in characterizing the nonlinear backbone curve of soils. Considering a soil to be purely hysteretic, the Bouc-Wen model of soil is written as

$$\dot{\tau} = A\dot{\gamma}_s - \beta|\dot{\gamma}_s||\tau|^{n-1}\tau - \gamma\dot{\gamma}_s|\tau|^n, \tag{A.81}$$

where τ = shear stress; $\dot{\gamma}_s$ = shear strain; A = initial shear stress modulus. For non-degrading soils, using $\beta = \gamma$ ensures that the backbone curve is convex and symmetric about the origin in this study. With $\beta = \gamma$ the time-rate form of the backbone curve is obtained from (A.81) as

$$\dot{\tau} = A\dot{\gamma}_s - 2\beta\dot{\gamma}_s|\tau|^n, \tag{A.82}$$

where A, β and n are the parameters to be identified.

Identification is first carried out based on soil hysteresis loops, using a weighted global iteration scheme for parameter identification consisting of the following steps:

1. Start the first run with estimates of the initial condition $\mathbf{X}(0|0)$ and its error covariance matrix, $\mathbf{P}(0|0)$.
2. Carry out the extended Kalman filtering of the data and obtain at the end of the analysis the updated estimates of $\hat{\mathbf{X}}(n|n)$ and $\mathbf{P}(n|n)$.
3. For the next iteration, use the obtained parameter, $\hat{\mathbf{X}}_p(n|n)$, as the new initial estimate, and scale the submatrix, $\mathbf{P}_{pp}(n|n)$, with a weighting factor w. The estimates of the initial conditions $\hat{\mathbf{X}}_s(0|0)$ and $\mathbf{P}_{ss}(0|0)$ are not modified in the iteration. For instance, after i iterations, the new initial estimates for the $i+1$ iteration is as follows:

$$\hat{\mathbf{X}}^{i+1}(\mathbf{0}|\mathbf{0}) = \begin{bmatrix} \hat{\mathbf{X}}^0_s(0|0) \\ \hat{\mathbf{X}}^i_p(n|n) \end{bmatrix} \tag{A.83}$$

$$\mathbf{P}^{i+1}(\mathbf{0}|\mathbf{0}) = \begin{bmatrix} \mathbf{P}^0_{ss}(0|0) & \mathbf{0} \\ \mathbf{0} & w \cdot \mathbf{P}^i_{pp}(n|n) \end{bmatrix} \tag{A.84}$$

4. Continue the analysis until the parameters can no longer be improved or a local minimum identification error is reached.

Reference [513] presents three algorithms based upon the simplex [35], extended Kalman filter [315], and generalized reduced gradient methods. The objective is to estimate the parameters of hysteresis for different classes of inelastic structures using the generalized Bouc-Wen model that accounts for degradation and pinching [27]. This model form contains 13 parameters to be identified and in which the restoring force is expressed as

$$F_r = \alpha k x + (1-\alpha) k z, \tag{A.85}$$

$$\dot{z} = h(z)\left\{\frac{A\dot{x} - \nu(\beta|\dot{x}||z|^{n-1}z + \gamma\dot{x}|z|^n)}{\eta}\right\}, \tag{A.86}$$

in which A, β, γ, n are simple loop parameters while ν, η are functions containing additional loop parameters as a function of the energy dissipated through hysteresis.

In [286], an adaptive on-line identification algorithm is proposed for parametric and non-parametric identification of structural models, and is applied to a generalized Bouc-Wen model. The proposed identification methodology, a recursive least-square (Kalman filter) based algorithm, upgrades the adaptation gain matrix using an adaptive forgetting factor that is expressed as the ratio between the minimum value of the diagonal elements of the adaptation gain matrix and a set of pre-defined threshold values. This approach requires only acceleration measurements.

A.6.3 Genetic algorithm based identification

In [168] a genetic based identification algorithm is proposed. The reproduction procedure adopts the roulette wheel selection and the method of crossover and uniform mutation [8, 174].

A modification to the standard Bouc-Wen model is proposed in [266] to account for non-symmetrical hysteresis exhibited by an MR damper

$$f = c\dot{x} + kx + \alpha z - f_0, \tag{A.87}$$

$$\dot{z} = \big(A - (\gamma + \beta\,\mathrm{sign}\,(z\dot{x})|z|^n)\big)(\dot{x} - \mu\,\mathrm{sign}\,(x)), \tag{A.88}$$

where f_0 is the initial damper displacement contributing to the force offset and μ is the scale factor for the velocity adjustment.

Then, the model parameters are identified by a genetic algorithm that is improved here by

1. Removing the selection stage (it is absorbed into the crossover and mutation operations).
2. Imposing a termination criterion on the basis of statistical tests which guarantees the quality of a near-optimal solution.

The parameters to be defined are c, k, f_0, α, A, β, γ, n and, μ. Hence, the chromosome becomes

$$C_i = \{c_i, k_i, f_{0,i}, \alpha_i, A_i, \beta_i, \gamma_i, n_i, \mu_i\}, \quad i = 1, \ldots, N, \quad N = 50 \tag{A.89}$$

The fitness function is designed from the averaged sum of normalized square error between the simulated and experimental data. That is

$$e_i = \frac{1}{n}\sum_{i=1}^{n} |\bar{v}_i| \left(\frac{f_i^{\mathrm{sim}} - f_i^{\mathrm{exp}}}{\Delta f}\right)^2 \tag{A.90}$$

where n = the number of data points, $\bar{v}_i \in [-1, 1]$ is the normalized velocity and $\Delta f = f_{\max} - f_{\min}$ is the difference in experimental force data.

Reference [267] proposes an identification method based on differential evolution using simulated noise-free data and experimental data obtained from a nuclear power plant. The Bouc-Wen model parameter n is kept constant to the value 2. The used objective function is the mean square error (MSE) which is cast in the discrete normalized form as

$$MSE = \frac{100}{n\sigma_{\ddot{x}}^2} \sum_{i=n}^{\bar{n}} \big(x(t) - \hat{x}(t|\underline{P})\big)^2, \tag{A.91}$$

where $\sigma_{\ddot{x}}^2$ = the variance of the measured output and n = the number of points in the measured output; x and $\hat{x}$ = the measured and predicted time history, respectively; and $\underline{P}$ = the parameter vector.

The optimization of the objective function is quoted from [368] and stated as obtaining the parameter vector $\hat{\underline{P}}$ which minimizes the MSE. The parameter vector is subjected to the constraint

$$\underline{P}_{\,\mathrm{min}} \quad \leq \quad \hat{\underline{P}} \quad \leq \quad \underline{P}_{\,\mathrm{max}} \tag{A.92}$$

The so-called direct search optimization methods do not usually provide a mechanism to restrict the parameters in the range defined by inequality (A.92); neither does the differential evolution. However, an unconstrained optimization method can be transformed to a constrained one using the concept of the *penalty function*. This function determines a penalty to be added to the value of the MSE any time any parameter exceeds the range limits. The penalty function selected for this case is given by

$$\mathrm{Penalty}(P_i) = \\ \begin{cases} 20\big((P_{i(\mathrm{min})} - P_i)/P_{(\mathrm{min})}\big)^2 & \text{for} \quad P_i < P_{i(\mathrm{min})} \\ 0 & \text{for} \quad P_{i(\mathrm{min})} < P_i < P_{i(\mathrm{max})} \\ 20\big((P_{i(\mathrm{max})} - P_i)^2/P_{i(\mathrm{max})}\big)^2 & \text{for} \quad P_i > P_{i(\mathrm{max})} \end{cases} \tag{A.93}$$

In [305], a population-search algorithm is proposed to estimate the 13 parameters of the generalized Bouc-Wen model. With a given load-displacement trace as input, the optimization problem can be stated as the determination of the parameter vector

$$\mathbf{p} = (A, \alpha, \beta, \gamma, n, \delta_\nu, \delta_\eta, \zeta_s, q, p, \psi, \delta_\psi, \lambda) \tag{A.94}$$

such that the objective function

$$g_N(\mathbf{p}) = \frac{1}{N} \sum_{j=1}^{N} [x(t_j) - \hat{x}(t_j|\mathbf{p})]^2 \tag{A.95}$$

is minimized, where N = the number of data points used. Minimization of the objective function is subject to the constraint that all parameters in $\mathbf{p}$ with the exception of γ are positive.

A.6.4 Gauss-Newton iterative based identification

In [492], a method of estimating the parameters of hysteretic Bouc-Wen model on the basis of possibly noise corrupted input-output data is proposed. The system model is

$$\ddot{x} + a\dot{x} + bx + z = f \tag{A.96}$$

$$\dot{z} = A\dot{x} - \beta|\dot{x}||z|^{n-1}z - \gamma\dot{x}|z|^{n} \tag{A.97}$$

The observations are assumed to be of the form

$$y = \ddot{x} + \varepsilon \tag{A.98}$$

where (i) ε is a zero mean Gaussian white noise with variance σ_e^2, (ii) the input f is zero mean Gaussian white noise and can be measured noise free, and further the input f is independent of the observation noise, (iii) the initial conditions are known and are set to zero for simplicity. Hence, the integrated mean squared error is selected for minimization as

$$Q = \frac{1}{T}\int_0^T \varepsilon^2 \,\mathrm{d}\,t = \frac{1}{T}\int_0^T \left[y - \ddot{x}\right]^2 \mathrm{d}\,t \tag{A.99}$$

with respect to the parameters a, b, A, β, γ, n. (A.99) is differentiated w.r.t. each parameter to get a system of normal equations

$$Q = \frac{1}{T}\int_0^T \left[y - \ddot{x}\right]\ddot{(\partial x/\partial\theta_i)}\mathrm{d}\,t = 0, \quad i = 1, 2, \ldots, 6 \tag{A.100}$$

that is solved using the Gauss Newton iterative procedure, where $\theta = [a\ b\ A\ \beta\ \gamma\ n]$.

In [280], Gauss-Newton iterations are used as a method of estimating the parameters of hysteretic system with slip on the basis of input-output data. The model used is called slip-lock [27] as an extended version of the Bouc-Wen model, and describes the pinching of hysteresis loops:

$$\ddot{x} + a\dot{x} + bx + z = p(t) \tag{A.101}$$

$$\dot{z} = A\dot{x}_1 - \beta|\dot{x}_1||z|^{n-1}z - \gamma\dot{x}_1|z|^{n} \tag{A.102}$$

$$\dot{x}_1 = \sqrt{\frac{2}{\pi}}\frac{s}{\sigma}\exp\left[-\frac{z^2}{2\sigma^2}\right]\dot{z} \tag{A.103}$$

$$x = x_1 + x_2 \tag{A.104}$$

$$s = \delta_s E(t) \tag{A.105}$$

where $s = \delta_s E$ is the slip, δ_s is a constant, E is the system energy dissipation; and $\sigma =$ the Gaussian density function. Then, the parameters to be identified are a, b, A, β, γ, n, δ_s and σ the elements of the column vector θ.

The basic philosophy of the identification method begins with the selection of the integrated mean squared error between the actual observation of acceleration $\hat{\ddot{x}}(t)$ and the model response $\ddot{x}(t)$ as a cost function for minimization, i.e.

$$\text{minimize } Q = \frac{1}{T} \int_0^T \left[\hat{\ddot{x}}(t) - \ddot{x}(t)\right]^2 \mathrm{d}\, t \tag{A.106}$$

with the parameters a, b, A, β, γ, n, δ_s and σ, where $T =$ the sampling time.

Since $\ddot{x}(t)$ is non-linear function in all the parameters, (A.106) can be solved iteratively. The Gauss-Newton iterative procedure is used as:

$$\theta_{m+1} = \theta_m - \tilde{H}_m^{-1} \nabla Q_m, \tag{A.107}$$

where $\tilde{H}_m =$ the Hessian matrix of Q, but only the first order derivative is used. $\nabla Q_m =$ the Jacobian vector of Q, and the subscript m denotes the computation of the matrix $\tilde{H}_m$ or the vector ∇Q_m with respect to the estimate of the parameter vector θ at the mth iteration.

A three-stage procedure is suggested for carrying out the iteration:

- In the first stage, the parameters n and σ are kept fixed and Q is minimized over the six parameters a, b, A, β, γ, and δ_s.
- In the second stage, the parameter σ is kept fixed and Q is minimized over the seven parameters a, b, A, β, γ, n, and δ_s.
- In the third stage, Q is minimized over all the eight parameters.

A.6.5 Bootstrap filter based identification

In [278], a parametric identification method is proposed for an extended form of the Bouc-Wen model that accounts for stick-slip phenomenon [27]. The method uses the bootstrap filter, a filtering method based on Bayesian state estimation and Monte Carlo method. Also, a method to decide the initial estimates of the parameters is suggested to obtain stable solutions as well as their fast convergence to the optimal values.

A.6.6 Identification using periodic signals

Reference [336] proposes a frequency domain parametric identification method of non-linear hysteretic isolators described by

$$m\ddot{x}(t) + r(t) = F(t), \tag{A.108}$$

$$r(t) = kx(t) + z(t), \tag{A.109}$$

$$\dot{z} = A\dot{x} - \beta|\dot{x}||z|^{n-1}z - \gamma\dot{x}|z|^n. \tag{A.110}$$

Assuming a known mass m, the hysteretic restoring force governed by (A.109) is identified by taking measurements of both the external excitation $F(t)$ and the displacement response $x(t)$ (or the acceleration $\ddot{x}$ alternatively). The vector of model parameters to be identified is $\{\mathbf{y}\} = \{k\,\alpha\,\beta\,\gamma\,n\}^T$.

The signals $F(t)$ and $x(t)$ are periodic and are expressed as

$$F(t) = \frac{F_0}{2} + \sum_{j=1}^{N} F_j \cos j\omega t + \sum_{j=1}^{N} F_j^* \sin j\omega t, \tag{A.111}$$

$$x(t) = \frac{a_0}{2} + \sum_{j=1}^{N} a_j \cos j\omega t + \sum_{j=1}^{N} a_j^* \sin j\omega t, \tag{A.112}$$

$$\text{where } \{\mathbf{F}\} = \{F_0\,F_1\,F_2 \cdots F_N\,F_1^*\,F_2^* \cdots F_N^*\}^T \tag{A.113}$$

$$\{\mathbf{a}\} = \{a_0\,a_1\,a_2 \cdots a_N\,a_1^*\,a_2^* \cdots a_N^*\}^T \tag{A.114}$$

ω is the vibration frequency and N is the order number of harmonics truncated. Applying the Galerkin (harmonic balance) method into the time domain determining function

$$\begin{aligned} D(t) = \dot{F} - m\dddot{x} - \dot{x}\{k + A \\ - [\beta \operatorname{sign}(\dot{x}) \operatorname{sign}(F - kx - m\ddot{x}) + y]|F - kx - m\ddot{x}|^n\} \end{aligned} \tag{A.115}$$

achieves

$$\mathbf{d}(\mathbf{y}) = \mathbf{0} \tag{A.116}$$

where $\{\mathbf{d}(\mathbf{y})\}$ is the residual of the equations and a minimization problem in terms of non-linear least squares arises as

$$\min g(\mathbf{y}) = ||\mathbf{d}(\mathbf{y})||^2 = \mathbf{d}^T\mathbf{d} \tag{A.117}$$

This non-linear least squares optimal problem is solved iteratively by the Levenberg-Marquardt algorithm.

In [201, 194], an identification method for the normalized Bouc-Wen model is proposed. Using the analytical description of the hysteresis loop developed in [200], an algorithm is proposed along with its analytical proof. It consists in exciting the Bouc-Wen model with two periodic signals with a loading-unloading shape (wave periodic) which gives rise asymptotically to a hysteretic periodic response. The obtained two limit cycles are then used as input to determine exactly the unknown parameters. The identification methodology is summarized in the following steps:

- STEP 1. Excite the Bouc-Wen model with a wave periodic signal $x(t)$. After a transient, the output $\Phi_{BW}(t)$ will have a steady state as $\bar{\Phi}_{BW}(t)$. Since both the input and the output are accessible to measurements, the relation $(x, \bar{\Phi}_{BW}(x))$ is known.

- Step 2. Choose a nonzero constant q and excite the Bouc-Wen model with the input $x_1(t) = x(t) + q$. After a transient, the output $\Phi_{BW,1}(t)$ will have a steady state $\bar{\Phi}_{BW,1}(t)$. Since both the input and the output are accessible to measurements, the relation $(x_1, \bar{\Phi}_{BW,1}(x_1))$ is known.
- Step 3. Compute the coefficient κ_x as

$$\kappa_x = \frac{\bar{\Phi}_{BW,1}(x+q) - \bar{\Phi}_{BW}(x)}{q}. \tag{A.118}$$

- Step 4. Compute the function $\theta(x)$ as

$$\kappa_w \bar{w}(x) = \bar{\Phi}_{BW}(x) - \kappa_x x \triangleq \theta(x). \tag{A.119}$$

- Step 5. Determine the unique zero of the function $\theta(x)$, that is the quantity x_* such that $\theta(x_*) = 0$
- Step 6. Compute the parameter a as

$$a = \left(\frac{d\theta(x)}{dx} \right)_{x=x_*}. \tag{A.120}$$

- Step 7. Choose two design constants x_{*1} and x_{*2} such that $x_{*2} > x_{*1} > x_*$. Then compute parameters n and b using the following equations

$$n = \frac{\log \left(\frac{\left(\frac{d\theta(x)}{dx} \right)_{x=x_{*2}} - a}{\left(\frac{d\theta(x)}{dx} \right)_{x=x_{*1}} - a} \right)}{\log \left(\frac{\theta(x_{*2})}{\theta(x_{*1})} \right)}, \tag{A.121}$$

  where log(.) denotes the natural logarithm

$$b = \frac{a - \left(\frac{d\theta(x)}{dx} \right)_{x=x_{*2}}}{\theta(x_{*2})^n}. \tag{A.122}$$

- Step 8. Compute the parameters κ_w and ρ as

$$\kappa_w = \sqrt[n]{\frac{a}{b}}, \tag{A.123}$$

$$\rho = \frac{a}{\kappa_w}. \tag{A.124}$$

- Step 9. Compute the function $\bar{w}(x)$ using

$$\bar{w}(x) = \frac{\theta(x)}{\kappa_w} \tag{A.125}$$

- STEP 10. Choose a design constant x_{*3} such that $x_{*3} < x_*$. Then compute the parameter σ as follows:

$$\sigma = \frac{1}{2}\left(\frac{\frac{\left(\frac{d\bar{w}(x)}{dx}\right)_{x=x*3}}{\rho} - 1}{(-\bar{w}(x_{*3}))^n} + 1\right). \tag{A.126}$$

A.6.7 Simplex method based identification

Reference [367] presents a two-step system identification approach that does not require the semiactive device to be tested apart from the structure, but rather mounted into it. It consists in (i) identification of a model for the primary structure without the semiactive damper attached; (ii) installation of the semiactive damper in the structure and simultaneous identification of the remaining parameters for the primary structure and of a model for the semiactive control device. The simplex algorithm is employed to optimize the dynamical parameters.

In [163], the simplex and Levenberg-Marquardt optimization methods are used to fit experimental data with curves given by a Bouc-Wen model in a dynamic suspension modeling problem.

A.6.8 Support vector regression based identification

Reference [515] proposes a non-linear structural identification scheme to identify the Bouc-Wen type structures. It produces the unknown power parameter n of the model by the model selection strategy, transforms the non-linear differential equation into a linear problem through the high order Adam Moulton implicit equation [386], and utilizes the support vector regression data processing technique to solve non-linear structural parameters.

A.6.9 Constrained nonlinear optimization based identification

Paper [383] uses the Bouc-Wen model to describe magnetorheological dampers, and proposes a methodology of identification to determine the model parameters. The value $n = 2$ is supposed and the model estimation problem is reduced to an optimization problem where the performance index is a classical normalized L_2-norm of the output fitting error.

In [466], [449] and [498] a constrained nonlinear optimization is used for identification purpose.

A.6.10 Non-parametric identification

In [317], the Bouc-Wen nonlinear hysteresis term is approximated by a power series expansion of suitable basis functions, then the coefficients of the functions are determined using standard least-squares methods.

In [295], a method relying on deconvolution to estimate the non-linear hysteretic force z from experimental records is used.

A.7 Modeling using the Bouc-Wen model

The Bouc-Wen model has been extensively adopted in many engineering fields to represent the hysteresis behavior of some nonlinear components. In this section, we present an overview of the use of this model.

A.7.1 Magnetorheological dampers

Magnetorhelological (MR) dampers are hysteretic devices that employ rheological fluids to modify their mechanical properties. The stiffness and damping characteristics of the MR damper change when the rheological fluid is exposed to a magnetic field. The Bouc-Wen model has been used to describe the hysteresis behavior of these devices.

Reference [126] proposes a non-linear model for MR damper which incorporates the current (I), amplitude and frequency excitation (ω) as input variables.

In this sense, the modified Bouc-Wen model is reformulated as follows:

$$F\big(x(\tau),\dot{x}(\tau),I,\omega,x,0\leq\tau\leq t;t\big) \tag{A.127a}$$

$$= \big(d_1\,\omega^{d_2}\big)\,\big(d_3\,\omega_{\max}^{d_4}\big)\,[c_0(I)\dot{x}+k_0(I)x+\alpha(I)z] \tag{A.127b}$$

$$\dot{z}(I) = A(I)\dot{x}+\beta(I)|\dot{x}||z|^{n-1}z-\gamma\dot{x}|z|^{n} \tag{A.127c}$$

$$c_0(I) = c_1+c_2\left(1-e^{-c_3(I-I_c)}\right) \quad \text{for } I>I_c \tag{A.127d}$$

$$c_0(I) = c_4+\frac{c_4-c_1}{I_c}I \quad \text{for } I\leq I_c \tag{A.127e}$$

$$k_0(I) = k_1+k_2\,I \tag{A.127f}$$

$$\alpha(I) = \alpha_1+\alpha_2\left(1-e^{-\alpha_3(I-I_c)}\right) \quad \text{for } I>I_c \tag{A.127g}$$

$$\alpha_0(I) = \alpha_1+\frac{\alpha_4-\alpha_1}{I_c}I \quad \text{for } I\leq I_c \tag{A.127h}$$

$$\beta(I) = \beta_1-\beta_2\,I \tag{A.127i}$$

$$F_{z0}(I) = F_{z01}+F_{z02}\left(1-e^{-F_{z03}(I-I_c)}\right) \quad \text{for } I>I_c \tag{A.127j}$$

$$F_{z0}(I) = F_{z04}+\frac{F_{z04}-F_{z01}}{I_c}I \quad \text{for } I\leq I_c \tag{A.127k}$$

where A and γ assumed to be one and zero, respectively, and the 16 constant parameters c_1, c_2, c_3, c_4, k_1, k_2, α_1, α_2, α_3, α_4, γ_1, γ_2, F_{z01}, F_{z02}, F_{z03} and F_{z04} relate the characteristic shape parameters to current excitation. I_c is the critical current in which the characteristic parameters change their linear behavior in low velocity to exponential behavior in high velocity.

Paper [341] presents a simple mechanical model consisting of a Bouc-Wen element in parallel with a viscous damper (with damping coefficient c_0). It was used and verified to accurately predict the behavior of a prototype shear-mode MR damper over a wide of range of inputs by. The force f exerted by this model is

$$f = c_0\,\dot{x}+\alpha\,z \tag{A.128}$$

where z is given by (A.139). Device model parameters α and c_0 are considered dependent on the control voltage V as follows:

$$\alpha = \alpha(V) = \alpha_a+\alpha_b\,V \tag{A.129}$$

$$c_0 = c_0(V) = c_{0a}+c_{0b}\,V \tag{A.130}$$

A Bouc-Wen hysteretic voltage-dependent model is developed from performance tests of a 3kN MR damper device that is incorporated to an isolated structure subjected to earthquake excitations in order to reduce its response by [299]. The restoring force $F(t)$ is expressed as

$$F(t) = C(V)\dot{x}+z \tag{A.131}$$

$$\dot{z} = A\dot{x}+\beta|\dot{x}||z|^{n-1}z+\gamma\dot{x}|z|^{n} \tag{A.132}$$

where $C(V)$ is a voltage-dependent parameter.

In [412], an extension to the standard Bouc-Wen model is proposed to account for the rolloff that appears in the force-displacement relationship at small velocities. In this modified model, the force is given by

$$F = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) = c_1\dot{y} + k_1(x - x_0) \tag{A.133}$$

where z and y are governed by

$$\dot{z} = -\beta|\dot{x} - \dot{y}|\, z\, |z|^{n-1} - \gamma(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \tag{A.134}$$

$$\dot{y} = \frac{1}{c_0 + c_1}\big(\alpha z + c_0\dot{x} + k_0(x - y)\big) \tag{A.135}$$

in which k_1 = accumulator stiffness; c_0 = viscous damping at large velocities; c_1 = viscous damping for force rolloff at low velocities; k_0 = stiffness at large velocities; and x_0 = initial displacement of spring k_1. This modification is used by [475] to reproduce the hysteresis loop of a large scale MR damper.

In [266], a non-symmetrical Bouc-Wen model for MR fluid dampers is presented. The adopted strategy is to adjust the velocity value in calculating the hysteretic variable but retain the general expression for the Bouc-Wen model. The resulting non-symmetrical Bouc-Wen model is

$$\dot{z} = \Big(A - \big(\gamma + \beta\,\mathrm{sign}[z(\dot{x} - \mu\,\mathrm{sign}(x))]\big)|z|^n\Big)(\dot{x} - \mu\,\mathrm{sign}(x)) \tag{A.136}$$

where μ is the scale factor for the adjustment, provided that

$$\mu\,\mathrm{sign}(x) \to 0\big|_{x\approx 0} \tag{A.137}$$

The overall effect is to shift the hysteresis switching in the vicinity of zero velocity while maintaining the hysteretic shape in the rest of the hysteresis loop.

Paper [476] presents a phenomenological dynamic model based on the Bouc-Wen model to estimate large-scale MR damper behavior under dynamic loading. This model accommodates the MR fluid stiction phenomenon, as well as fluid inertial and shear thinning effects. Moreover, the proposed model is supposed to be more effective in describing the force rolloff in the low velocity region, force overshoots when velocity changes in sign, and two clockwise hysteresis loops at the velocity extremes. The damper force is given by

$$f - f_0 = m\ddot{x} + c(\dot{x})\dot{x} + kx + \alpha z \tag{A.138}$$

$$\dot{z} = A\dot{x} - \beta|\dot{x}||z|^{n-1}z - \gamma\dot{x}|z|^n \tag{A.139}$$

In this model, m = equivalent mass which represents the MR fluid stiction phenomenon and inertial effect; k = accumulator stiffness and MR fluid compressibility; f_0 = damper friction force due to seals and measurement bias; and $c(\dot{x})$ = post-yield plastic damping coefficient which is defined as a monodecreasing function with respect to absolute velocity $|\dot{x}|$ to describe the MR fluid shear thinning effect which results in the force rolloff of the damper resisting force in the low velocity region. The post-yield damping coefficient is assumed to have the form

$$c(\dot{x}) = a_1 \, e^{-(a_2|\dot{x}|)^p} \tag{A.140}$$

where a_1, a_2 and p = positive constants.

In [498] and [341], a Bouc-Wen based phenomenological model of a shear-mode MR damper is presented while [193] proposes a simplified version of the Bouc-Wen model for MR dampers called the Dahl model.

A.7.2 Structural elements

The Bouc-Wen model has been used to simulate a variety of hysteretic structural elements behaviors. For example, and based on the modification of the Bouc-Wen-Baber-Noori model, general features of the hysteretic behavior of wood joints (with yielding plates or yielding nails or yielding bolts) and structural systems were characterized by [148]. The model accounts for degradation and pinching in the form:

$$\dot{z} = h(z) \left\{ \frac{A\dot{x} - \nu(\beta|\dot{x}||z|^{n-1}z + \gamma\dot{x}|z|^n)}{\eta} \right\} \tag{A.141}$$

where ν and η are the strength and stiffness degradation respectively.

In [344], the standard form of the model is incorporates into ABACUS to investigate the dynamic frictional contact of a bolted joint under harmonic loading.

Reference [448] investigates the effects of connection failure on structural response of steel buildings under earthquakes, a smooth connection-fracture hysteresis model based on the Bouc-Wen model. The form of the model that accounts for degradation is extended to represent asymmetric smooth hysteresis in which the ultimate positive and negative restoring forces are not equal. This extensions is formulated as

$$\dot{z} = \frac{\dot{x}}{\eta} \left(A - \nu|z|^n \left[\beta \, \mathrm{sign}(\dot{x}z) + \gamma + \phi(\mathrm{sign}(z) + \mathrm{sign}(\dot{x})) \right] \right) \tag{A.142}$$

in which ϕ is an additional parameter accounting for the asymmetric yielding behavior. The hysteresis loops shift downward or upward depending on the sign (positive or negative) of the parameter ϕ.

The inelastic behavior of connections is described in [281], taking into account capacity uncertainties of connections.

The work in [34] utilizes the Bouc-Wen model to describe hysteretic dampers that interconnect two adjacent structures subjected to seismic excitation.

Paper [29] studies the nonlinear response of single piles under lateral inertial and seismic loads using equation (A.144) as a macroscopic model. This model consists of distributed nonlinear springs (described by the Bouc-Wen model), combined with a distributed viscous (frequency dependent) dashpots, placed in parallel, and describes the lateral soil reaction. The variable y represents the value of pile deflection that indicates yielding in the spring.

A.7.3 Base isolation devices

The base isolation devices aim to absorb or reflect the earthquake input energy to the structure to keep linear structural vibration. Many devices are strongly nonlinear showing different hysteretic behaviors. The Bouc-Wen model has been introduced for its intrinsic ability in reproducing a wide range of real devices behavior.

A combined energy dissipation system was developed by [303]. In this system lead rubber dampers and their parallel connection with oil dampers are used in the braces of a structural frame. The restoring force characteristics of the lead rubber damper is simulated by the Bouc-Wen hysteretic model having the following form:

$$F = \alpha \frac{F_y}{d_y} x + (1-\alpha) F_y z \tag{A.143}$$

$$\dot{z} = \frac{1}{d_y} \left(A\dot{x} - \beta |\dot{x}| |z|^{n-1} z - \gamma \dot{x} |z|^n \right) \tag{A.144}$$

where F_y and d_y are the yielding force and yielding displacement, respectively.

The same form of (A.144) was also used to control the evolutionary parameter z by [106] to model the friction of Teflon-steel interfaces in sliding-based seismic isolation devices. The frictional force is given by

$$F_f = \mu_s W z \tag{A.145}$$

where μ_s is the coefficient of sliding friction, W is the structural weight, z takes values ±1 during sliding (yielding) and during sticking (elastic behavior), the absolute value of z is less than unity. Equation (A.144) was also used by [115] to model the dissipated energy by the wire rope isolators for building equipment, which have found numerous application in the shock and vibration isolation in military and industrial fields.

Because of its versatility and suitability for direct closed form stochastic linearization, the Bouc-Wen model was employed within a method of random vibration analysis of base isolated shear structures with hysteretic dampers by [107] and [312] to simulate the load deformation path of the hysteretic devices.

In [314], a parametric stochastic analysis of an isolated bridge is proposed with the aim to assess isolation performance and to investigate effects of energetic influence on protection efficiency. Isolated bridge (piers and seismic isolators) is described by a simple two degree of freedom Bouc-Wen hysteretic model. Engineering mechanical quantities were related to the analytical parameters of the model in order to model real structural elements. Accordingly, the evolutionary parameter z is given by

$$\dot{z} = \dot{x}\left[1 - \frac{1}{2}\left(\frac{z}{x_y}\right)^n (1 + \mathrm{sign}(z\dot{x}))\right] \tag{A.146}$$

$$x_y = \left(\frac{1}{\beta + \gamma}\right)^{1/n}, \quad \text{the limit elastic displacement} \tag{A.147}$$

assuming $A = 1$. It was reported that, by adopting the Bouc-Wen and by using appropriate parameters for this model, it becomes able to suitably characterize an ordinary building and the considered base isolators.

A.7.4 Mechanical systems

The Bouc-Wen model provides useful predictions of the responses of suspension seats of the off-road machines to transient inputs [163]. It is concluded that the Bouc–Wen model can provide a useful simulation of an existing seat and assist the optimization of an individual component in the seat, without measuring the dynamic properties of components in the seat except those of the component being optimized. The used form of the model is

$$\dot{F}_{BW} = (k - k_s)\dot{x} - \beta|\dot{x}|F_{BW} - \gamma\dot{x}|F_{BW}| \tag{A.148}$$

in which k and k_s are positive stiffnesses, x is the relative vertical displacement, while β and γ give the effect of hysteresis, and F_{BW} is the Bouc-Wen force that combines all the non-linear effects due to the different seat components.

Reference [406] investigates the interaction effect between electrical substation equipment (an important element within the power transmission lifeline) items connected by nonlinear rigid bus conductors. The symmetric hysteretic behaviors are described by the original Bouc-Wen model while the components having asymmetric hysteresis are modeled by a modified version of the Bouc-Wen model for highly asymmetric hysteresis loops with constant parameters. The auxiliary differential equation of this modified model is given as

$$\dot{z} = \dot{x}\left[A - |z|^n \psi(x, \dot{x}, z)\right] \tag{A.149}$$

$$\psi = \beta_1 \operatorname{sign}(\dot{x}z) + \beta_2 \operatorname{sign}(x\dot{x}) + \beta_3 \operatorname{sign}(xz) + \beta_4 \operatorname{sign}(\dot{x}) + \beta_5 \operatorname{sign}(z) + \beta_6 \operatorname{sign}(x) \quad \text{(A.150)}$$

in which $\beta_i, i = 1, 2, \ldots, 6$, are parameters controlling the shape of the hysteresis loop and x is the relative displacement.

To predict correctly the lateral vibration of an elevator in motion by [454], it was necessary to deal with a rate-dependent stick-slip phenomenon which may occur at a rubber-to-metal interface which is observed at the interface between the guide roller and the rail of a typical elevator in motion. To consider the rate-dependent nonlinearity, the mth-power velocity damping model $c|\dot{x}|^m \operatorname{sign}(\dot{x})$ is incorporated to the Bouc-Wen model, so the variable z is expressed as

$$z_m = c|\dot{x}|^m \operatorname{sign}(\dot{x}) + z, \quad \text{(A.151)}$$

where z is given by (A.139).

Without introducing any modifications to the standard Bouc-Wen model, an investigation of the dynamics of a small non-linear oscillator having softening hysteretic characteristic and weakly coupled with a linear oscillator was performed by [272].

A.7.5 Piezoelectric actuators

The Bouc-Wen model was experimentally modified by [300] to describe the hysteresis phenomenon of the piezoelectric actuator and used later by [167] and [284] to simulate the hysteresis of a piezoelectric element. The modified form is

$$\dot{z} = \alpha\, d_{33}\dot{V} - \beta|\dot{V}|z - \gamma\dot{V}|z|, \quad \text{(A.152)}$$

where d_{33} is the piezoelectric coefficient and V denotes the input voltage. α, β and γ control the shape of the hysteresis loop. The same form of the Bouc-Wen model was also employed to describe the frictional hysteresis force of an impact drive mechanism by [166].

A.7.6 Soil behavior

In a study of the grain-crushing-induced landslides, [158] used the hysteretic stress-strain Bouc-Wen-type constitutive model in conjunction with a Mohr-Column friction law and Terzaghi's effective stress principle to model the hysteretic stress-displacement relationship of the soil inside the shear band τ where,

$$\tau = \tau_y\, z, \quad \text{(A.153)}$$

in which τ_y = the ultimate shear strength and z is given by:

$$\dot{z} = \frac{1}{x_y}\bigl(1 - |z|^n \bigl[b + (1-b) \operatorname{sign}(\dot{x}z)\bigr]\bigr) \quad \text{(A.154)}$$

where $\dot{x}$ is the lateral velocity, x_y is a parameter accounting for the elasto-plastic slip tolerance and the parameter b controls the shape of the unloading-reloading curve. Its range of values is between 0 and 1.

Another extension to the Bouc-Wen hysteresis model is performed in [360] to provide a better representation of the actual shearing stress-strain behavior of soils under constant and variable amplitude cyclic loading. In particular, it is desired to obtain a better representation of the soil response under small amplitude non-symmetric and non-zero mean loading reversals. Simultaneously, it is also desired to obtain a better representation of the equivalent viscous damping ratio at high strain levels. The smooth-hysteretic model can be obtained if a finite number p of nonlinear-hysteretic springs described by the standard Bouc-Wen model are used in parallel, then the shearing stress τ is given by

$$\tau = (1-\alpha) G_m \gamma_s + (1-\alpha) \sum_{p=1}^{M} G_{m_p} z_p \tag{A.155}$$

$$\dot{z}_p = A_p \dot{\gamma}_s - \beta_p |\dot{\gamma}_s| |z_p|^{n_p - 1} z_p - \gamma_p \dot{\gamma}_s |z_p|_p^n \tag{A.156}$$

with the following conditions:

$$\sum_{p=1}^{M} G_{m_p} = G_m \tag{A.157}$$

$$\sum_{p=1}^{M} \tau_{m_p} = \tau_m \tag{A.158}$$

$$\tag{A.159}$$

where

$$\tau_{m_p} = G_{m_p} \left(\frac{A_p}{\beta_p + \gamma_{sp}} \right)^{1/n_p} \tag{A.160}$$

in which G_m is the (small strains) shear modulus; γ_s is the shearing strain; and τ_{mp} is the maximum shear stress.

A discrete version of the Bouc-Wen model to describe strong ground motion in Iceland is used in [343].

A.7.7 Energy dissipation systems

In [388], a modification of the Bouc-Wen model was proposed by adding the isotropic hardening mechanism to reproduce the nonlinear strain hardening in seismic resistance of rhombic Low Yield Strength Steel under practical reciprocating loading test. The modified form is

$$\dot{z} = A\dot{x} - \eta\big(\beta|\dot{x}||z|^{n-1}z + \gamma\dot{x}|z|^n\big) \tag{A.161}$$

$$\eta = \left(\frac{\Delta_y}{\Delta_{y0}}\right)^{-n} \tag{A.162}$$

$$\Delta_y = \begin{cases} \Delta_{y0} & \text{if } \Delta_{\max} \leq \Delta_{y0}, \\ \Delta_{y0} + \mu(\Delta_{\max} - \Delta_{y0}) & \text{if } \Delta_{\max} \geq \Delta_{y0}, \end{cases} \tag{A.163}$$

where Δ_{y0} is the initial yielding displacement; $\Delta_{\max}$ is the absolute value of the maximum displacement in the loading history; $\mu = \alpha - \nu$; ν is the rate of kinematic transformation; and η ranges from 0 to 1 and follows the transformation of deformation history, which is decreasing.

Based on the extension of the Bouc-Wen model that accounts for degradation, (A.141) with $h(z) = 1$, a friction energy dissipating system attached to reinforced concrete panel is studied. The extension of the Bouc-Wen model is employed to model the flexibility of the connection between the steel elements and the concrete panel, and to model the impact of these bolts as well as the expansion of the concrete holes as a result of the impact. It is concluded that, when modeling friction using elements that are based on the Bouc-Wen model, the violation of the model to Drucker and Iliushin postulates increases the displacement by an insignificant amount over some paths and has negligible effect on the predicted behavior, [382].

A.8 Conclusion

This chapter surveyed the literature related to the Bouc-Wen model. It has been organized into sections that address specific issues like modeling, control, identification, etc. Each section presented what, in the author's point of view, are the main contributions relative to that specific issue. It has not been possible to present every single work relative to the Bouc-Wen model as issues discussed in some papers are very peculiar and do not fall within any general category. Nevertheless, all the papers that the authors are aware of have been cited in the reference part of this survey. ■

$\bar{w}(\bar{x})$ with $\bar{x} \geq 0$	0		$\uparrow$		1
δ	0				$+\infty$
$\bar{w}(\bar{x})$ with $-1 < \bar{x} < 0$	0	$\downarrow$	$\bar{w}(\bar{x})_{\delta=\delta^*}$	$\uparrow$	1
δ	0		$\delta^* = \varphi_{\sigma,n}\left(\sqrt[n]{\frac{-\bar{x}}{\sigma\left(\bar{x}+1\right)-\bar{x}}}\right)$		$+\infty$
$\bar{w}(\bar{x})$ with $\bar{x} = -1$	0		$\downarrow$		-1
δ	0				$+\infty$
$\bar{w}(\bar{x})$ with $\bar{x} \geq \frac{2}{\delta}\psi_{\frac{1}{2},n}\left(\delta\right)-1$	$\bar{w}(\bar{x})_{\sigma=\frac{1}{2}}$		$\uparrow$		$\psi_n^+\left(\frac{\delta}{2}\left(\bar{x}+1\right)\right)$
σ	$\frac{1}{2}$				$+\infty$
$\bar{w}(\bar{x})$ with $\bar{x} < \frac{2}{\delta}\psi_{\frac{1}{2},n}\left(\delta\right)-1$	$\bar{w}(\bar{x})_{\sigma=\frac{1}{2}}$				$\psi_n^+\left(\frac{\delta}{2}\left(\bar{x}+1\right)\right)$
σ	$\frac{1}{2}$				$+\infty$
$\bar{w}(\bar{x})$	$\bar{w}(\bar{x})_{n=1}$				$\begin{cases} \text{if } \delta \in (0,2] & \frac{\delta}{2}\bar{x} \\ \text{if } \delta > 2 & \begin{cases} -1+\frac{\delta}{2}\left(\bar{x}+1\right) & \text{for } -1 \leq \bar{x} < \frac{4}{\delta}-1 \\ 1 & \text{for } \frac{4}{\delta}-1 \leq \bar{x} \leq 1 \end{cases} \end{cases}$
n	1				$+\infty$

Table A.4: Variation of the hysteretic output $\bar{w}(\bar{x})$ with the normalized Bouc-Wen model parameters.

B

Used softwares

The following list of computer softwares were efficiently used for the preparation of this dissertation in the present form:

- ANSYS 11
- SAP2000 11
- LaTeX2.7
- AutoCAD 2008
- SolidWorks 2008
- Matlab R2007b
- Photoshop 10 CS3
- Excel 2007
- WinEdt 5.5
- NONLIN 7.05
- SnagIt 9.10
- JabRef 2.42 ■

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