Multi-loop Hysteresis and Recursive Remnant Control

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Chapter 1

Introduction

Equipped with his five senses, man explores the universe around him and calls the adventure Science.
—Edwin Powell Hubble

Hysteresis is a natural phenomenon that was originally investigated by Ewing in 1882 in his work [18]. By applying alternating currents to a cable and measuring its magnetization and torsion, he observed a tendency of the magnetization to follow the torsion at the distance. To describe this lagging, he coined the term ”hysteresis” from the Greek $\breve{\upsilon}\sigma\tau\varepsilon\rho\acute{\varepsilon}\omega$ which means “to come after.” In the present days, hysteresis phenomena have been found and well-documented in various disciplines: from biology [3, 50], physics [11], astronomy [12], economics [5] to experimental psychology [55]. Due to its intrinsic complexity, hysteresis has attracted the attention of scientists. Moreover, the multitude of domains where it is present has led most of the efforts in describing it by so-called phenomenological models, i.e. models that describe its behavior mathematically without considering specific physics laws that underpin it. Of relevance due to their broadness and extension, we refer to [43] on the mathematical models of hysteresis and a treatment consisting of three volumes in [7], where extensive analysis and properties of hysteresis models are presented. Another important work is [11] where analysis and fundamental mathematical framework of hysteresis operators and their memory properties are introduced. The aforementioned works are related mainly to the so-called Preisach models, which are infinite-dimensional operators-based models. Another mathematical treatment of hysteresis can be found in [78] where the use of discontinuous differential equations are also considered.

1.1 Hysteresis loops

One of the main characteristics of systems exhibiting hysteretic behavior can directly be seen in their input-output phase plot. When oscillating inputs are applied to a hysteretic system, one can distinguish loops in the quasi-static input-output phase plot [6, 46, 46].

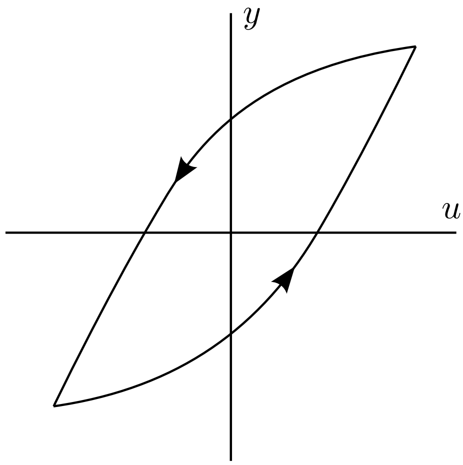


Figure 1.1: An illustration of a simple hysteresis loop that typically describes the relation between polarization and electric fields of piezoelectric materials or the relation between magnetization and magnetic field of magnetostrictive materials.

An illustrative example of one of the simplest classes of hysteresis loop that can be found in literature is shown in Fig. 1.1. This class of single-oriented loops occurs, for instance, in the relation between polarization and electric field of piezoelectric materials or the relation between magnetization and magnetic field of magnetostrictive material. More intricate hysteresis loops can also be found in literature, such as the so-called butterfly hysteresis loops [36,37,62,82], which occurs in their relation between strain and electric field of piezoelectric materials and their relation between strain and magnetic field of magnetostrictive materials. These convoluted hysteresis loops usually consist of two sub-loops with different orientation. An illustrative example is included in Fig. 1.2.

In literature, the behavior of hysteretic systems has been studied based on the class of curves that it produces in the input-output phase plots. For instance, we can find works that relate the orientation of the hysteresis loops (clockwise or counter-clockwise) to systems properties such as dissipativity and its special case passivity. Such properties are well-known in the literature of systems and control due to its relation to energy properties in physical systems and its usefulness in the analysis, design and interconnection of control systems. For instance, the dissipativity and passivity of the Preisach hysteresis operator [58] are proven in [19] with respect to a storage function constructed from its weighting function and the so-called interface, which is a curve that describes the memory state of the operator. Based on this characterization, stability analysis and control of smart actuators exhibiting hysteresis have been addressed in [20]. Analogous works can be found regarding dissipativity and passivity of the Duhem hysteresis operator in [27–29]. In this case, the storage functions are constructed from the so-called

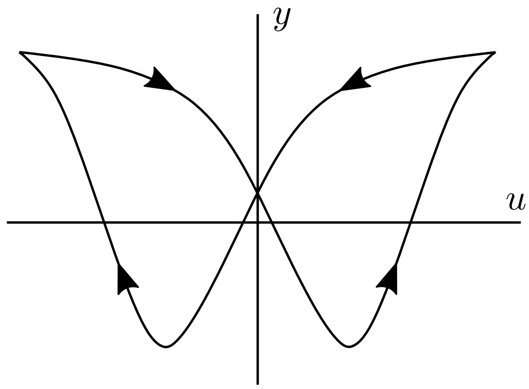


Figure 1.2: An illustration of a butterfly loop that can describe the relation between strain and electric field of piezoelectric materials or the relation between strain and magnetic field in magnetostrictive materials.

transversing and intersecting functions, which are related to the vector field that composes the discontinuous differential equation of the model. In [56] a modified Bouc–Wen model is studied, which has a monotonic input-output behavior and can describe a particular class of asymmetric double hysteresis loops by introducing position and/or acceleration information into the model equations. Moreover, it has been shown in [57] that when the parameters of this modified Bouc-Wen model satisfy particular conditions, the passivity property holds. A general framework for studying butterfly hysteresis loops is presented in [15]. The framework constructs the butterfly loops from single-oriented loops by applying the output of the hysteresis model through a convex function, which enforces the inflection points of the butterfly loop to have the same minimum. Furthermore, in [22], a specific form of the Duhem model proposed by [4] is studied, which can describe multiple-loop hysteresis behavior.

1.2 Remnant control of hysteretic systems

Usually, the presence of hysteresis in systems such as high-precision electro-mechanical systems or actuators compromises the precision and makes the modeling and design of control strategies more difficult. For this reason, in the literature of systems and control theory, a number of methods have been proposed and studied to control nonlinear systems containing hysteretic sub-systems or elements. For instance, when the hysteretic element can be modeled by a classical (rate-independent) Preisach operator, a standard brute-force approach involves the identification and the use of an inverse model that can approximately cancel the hysteresis non-linearity when it is connected in cascade [25].

A similar approach, based on a multiplicative structure, that does not require a direct inversion of a rate-dependent version of the Prandtl–Ishlinskii operator is presented in [1]. Other approaches exploit particular systems' properties and structure of the hysteresis model in order to design the stabilizing controller and to facilitate the analysis of the closed-loop systems. In this case, the aforementioned properties of dissipativity and passivity in hysteresis operators are particularly useful.

The common characteristic of the control strategies mentioned above is that they try to compensate for the hysteresis phenomenon effects on the system such that performance is not heavily compromised. Nevertheless, there exists a novel class of systems and actuators in which the presence of hysteresis is not undesired and instead is part of their fundamental working principle. In this class of systems, the memory effect of the hysteresis is exploited such that a particular state or configuration can be held even when the system input is removed. Roughly speaking, the working principle of this class of systems is that the control input is applied momentarily while the output achieves a value that will be held (partially) and subsequently the input is removed or set to zero again. An example of a system that uses this principle can be found in [30, 45], where a piezoelectric actuator that can held two stable configurations is presented. Moreover, a commercial hysteretic piezoelectric actuator, so-called PIRest, is developed and presented in [60].

When dealing with this class of systems, the objective is then to design a controller for regulating the output remnant value, which is the leftover memory for zero input, to the desired state. Considering that the hysteretic behavior is described by hysteresis operators, the remnant control problem is then based on controlling their memory property. Since the hysteresis memory-effect depends on the history of the applied input signal, the output remnant value can be driven from a given initial value to the desired one by a suitable input signal that is compactly defined (i.e., it has zero value outside a compact time interval). In general, the set-point regulation of output remnant via a compactly-defined input signal is relevant for applications that require minimal use of control input due to, for instance, input energy constraint or the associated energy loss/heat dissipation when a constant non-zero input is used to maintain the desired output. Moreover, the remnant control problem is also an essential part of the working principle of a new concept of a deformable mirror for space application described below.

1.2.1 Deformable mirrors and the HDM concept with remnant control

Deformable mirrors are instruments used in adaptive optics systems to correct light wavefront aberrations. The fields where they find application are diverse, such as microscopy, ophthalmology [49, 63], optical communications [54], high-power lasers [33] and astronomical instrumentation [41]. The working principle of a deformable mirror is simple: it cancels the aberrations by deflecting its surface such that the negative of the wavefront distortion is introduced. The surface deflection can be achieved by means of different actuation mechanisms, for instance, bimorphs [48, 67], MEMS [8], voice-coil actuators [61], among others [75]. When smart-materials and MEMS are used as actuation mechanisms, it is common that non-linearities in the behavior of the actuators arise [81]. Particularly, piezoelectric-based actuators can exhibit hysteresis which in deformable mirrors (as well as in other classes of high-precision electro-mechanical systems) is usually a non-desired phenomenon, and the prevailing approach is then trying to compensate it or cancel it such as in [39, 80].

Nevertheless, a novel class of deformable mirrors whose operation is based on the principle of remnant control has been presented in [21]. The actuator of this deformable mirror consists of wafers of piezoelectric material purposely designed to exhibit high asymmetric hysteresis behavior, which looks to maximize the range of the output remnant [26,65,76]. The concept enables a high-density of actuators via time multiplexing of the input with almost no heat dissipation [65] and has been called Hysteretic Deformable Mirror (HDM). Therefore, exploiting the hysteresis, the HDM goal is to achieve and hold a desired surface deflection for long time periods without the necessity of an individual constant control input for every actuator.

Different challenges arise in the HDM concept. Of relevance for the control strategy design, a cross-talked effect among the actuators inputs has been shown in [21, 64] by FEA analysis. Therefore, the remnant control strategy for the HDM presents an additional difficulty that can, in fact, be tackled by exploiting the so-called wiping-out property of the hysteresis [43]. To illustrate the remnant and the wiping-out property in an experimental form, Fig. 1.3 shows electric-field and strain measurements taken by a laser interferometer from a piezoelectric material sample made out of doped Lead Zirconate Tinate (PZT) [76]. The sample exhibited highly asymmetric butterfly hysteresis behavior. The signals are explained briefly below. Note from the input voltage shown in Fig. 1.3a that in the time interval between 0 and 2 seconds, an initialization signal is applied to the sample in order to obtain an initial relative thickness used as zero reference. Subsequently, between 3 and 3.5 seconds, one triangular pulse of $1000V$ is applied. It can be observed in the strain of Fig. 1.3b that after the voltage is zero again, the strain remains in a constant value close to the $350nm$. This is the so-called remnant caused by hysteresis. Afterwards, between 4.5 and 5 seconds, a second triangular pulse of $600V$ is applied. Note that the second pulse causes a momentary change in the strain of the sample. However, once the voltage is zero again, the remnant remains at the same value of approximately $350nm$ set by the first triangular pulse. This is the effect of the wiping-out property. In other words, due to the wiping-out property only the dominant extrema of the input affect the remnant value [43]. Using this property, the HDM remnant control can be solved, and the desired surface deflection can be achieved by activating the actuators in a sequential manner.

1.3 Contributions of this thesis

1.3.1 Butterfly and multi-loop Preisach hysteresis operator

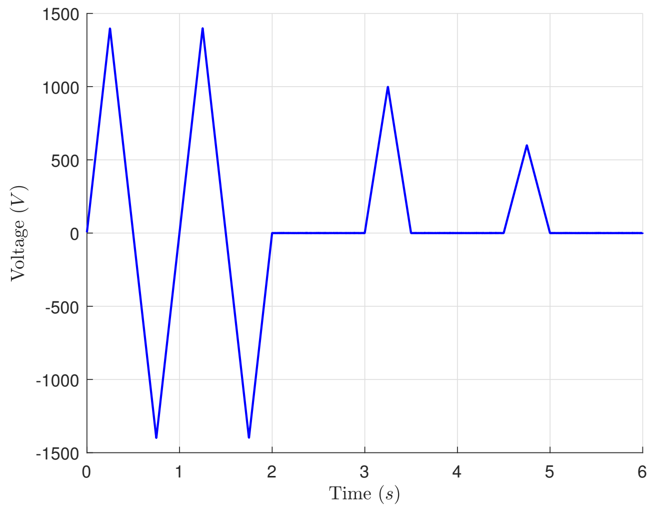
In Chapter 3, we introduce a class of Preisach hysteresis operators that we have denominated as Preisach butterfly hysteresis operators due to its capability to describe hysteresis loops. The contents of this chapter are based on the published paper [74]. We provide an analysis of the distribution of the positive and negative domains of the weighting function of this class of Preisach hysteresis operator and state sufficient conditions for the existence of butterfly hysteresis loops in the input-output phase plot under the application of periodic inputs. Furthermore, we show that hysteresis loops with more than one self-intersection can be obtained from a Preisach hysteresis operator whose weighting functions have a complex distribution of positive and negative domains, under some additional mild assumptions.

1.3.2 Absolute stability with butterfly and multi-loop Preisach hysteresis operator

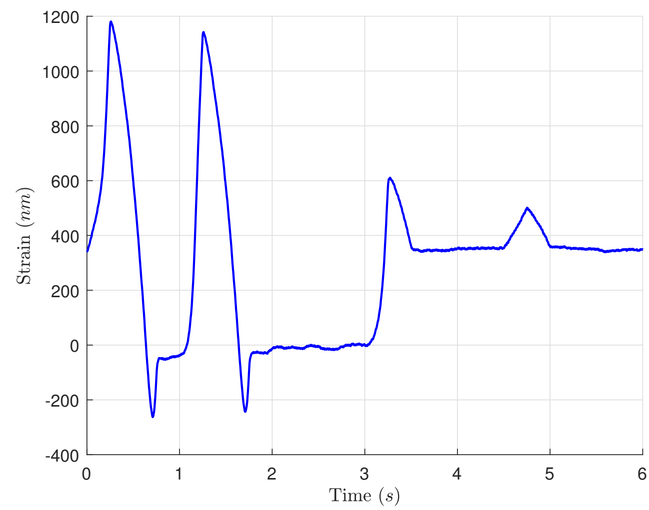
The contents of Chapter 4 are based on the published paper [70]. Following from the previous chapter, we present an analysis of the Preisach hysteresis operators this time in the context of the stability of the feedback interconnection with a linear system. This is the classic problem of the so-called Lur'e system [35]. Firstly, we find an explicit expression for the Preisach hysteresis operator output rate as a proportional time-varying relation with the input rate. Later, using this expression and considering that the Preisach hysteresis operator has a compactly supported weighting function, we provide conditions for the set stability of the feedback interconnection.

1.3.3 Butterfly and multi-loop Duhem operator

In Chapter 5, we study the Duhem hysteresis operator. The contents are based on the paper [71]. We begin analyzing the so-called accommodation property of the Duhem hysteresis operator [69], which roughly speaking corresponds to the convergence of the input-output phase plot to a periodic closed orbit when a periodic input is applied to it. We extend the results from [22] in the sense that we present a reduced pair of conditions for the existence of a periodic solution to the discontinuous differential equation



(a) Voltage applied to the piezoelectric sample.



(b) Strain of the piezoelectric sample.

Figure 1.3: Strain measurements of a piezoelectric sample where the remnant can be observed.

that composes the Duhem model, when the input is periodic. Moreover, based on the conditions for the existence of periodic solutions, we present a class of Duhem models that exhibits butterfly loops as well as loops with more than one self-intersection in its input-output phase plot.

1.3.4 The remnant control

The contents in Chapter 6 are based on the publication [72]. We introduce the formulation of the remnant control problem for systems whose hysteretic behavior can be described by the Preisach hysteresis operator and the Duhem hysteresis operator. We define the remnant as the value of a hysteresis operator output that is maintained whenever its input is set to zero. Roughly speaking, our remnant control problem consists of designing an strategy and an input signal for the hysteresis operator such that its remnant can be regulated to a desired reference value. To solve this problem, we define the input as a train of triangular pulses of modulated amplitudes which are found by a recursive control algorithm. In this form, the remnant reference is approached in an iterative fashion with asymptotic convergence. We also present conditions to guarantee the convergence of the output remnant to the remnant reference and present numerical simulations based on piezoelectric hysteretic behavior described by a Preisach butterfly hysteresis model and a class of Duhem models known as the Miller model.

1.3.5 The HDM concept remnant control

In Chapter 7, we integrate the results presented in [73], [65] and [21]. The contents we present are an extension of the remnant control problem for the novel concept of a Hysteretic Deformable Mirror (HDM) which have been also presented in [21]. We introduce a quasi-static modeling approach for the platform. We integrate the thin plate mirror model described by Poisson's equation and an electro-mechanical model of the hysteretic piezoelectric actuators composed of Preisach hysteresis operators. The control problem in the HDM introduces the difficulty of electrically-coupled inputs in the actuators due to the particular electrodes layout and interconnection. We present conditions such that the remnant of the actuators can be regulated to their desired reference such that the whole mirror plate attains the desired surface deflection.

1.4 List of publications

Journal papers

- M. A. Vasquez Beltran, B. Jayawardhana and R. F. Peletier. On the characterization of butterfly and multi-loop hysteresis behavior. IEEE Transactions on Automatic Control, doi: 10.1109/TAC.2021.3109533. 2021.
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- M. A. Vasquez-Beltran, B. Jayawardhana, R. F. Peletier. Iterative Algorithm for the Distributed Remnant Control of a Hysteretic Deformable Mirror. IEEE Transactions on Control Systems Technology. 2021. In preparation.

Conference papers

- Jayawardhana, B., Vasquez Beltran, M. A., van de Beek, W., de Jonge, C., Acuautla Meneses, M. I., Damerio, S., Peletier, R., Noheda, B., Huisman, R. Modeling and analysis of butterfly loops via Preisach operators and its application in a piezoelectric material. 57th IEEE Conference on Decision and Control. IEEE, p. 6894-6899 8 p. 2019.