Multi-loop Hysteresis and Recursive Remnant Control

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Chapter 8

Conclusions and Open Problems

You can't connect the dots looking forward; you can only connect them looking backwards. So you have to trust that the dots will somehow connect in your future.
—Steve Jobs

8.1 Conclusions

This thesis discussed the modeling of complex hysteretic behavior and applications to remnant control. In particular, we studied the modeling of butterfly hysteresis loops via the Preisach hysteresis operator and the Duhem hysteresis operator. We characterized conditions for both models such that they exhibit butterfly hysteresis loops. Moreover, we showed that complex multi-loop hysteresis behavior can also be obtained from both models when the conditions imposed, respectively, are relaxed.

In Chapter 3, the Preisach butterfly hysteresis operator was defined based on the existence of a hysteresis loop in its input-output phase plot whose enclosed area was zero. In other words, a butterfly hysteresis operator exhibits at least one hysteresis loop composed of sub-loops with different orientations such that the total enclosed area in the input-output phase plot was zero. Furthermore, it was shown that the structure of its weighting function and the distribution of positive and negative domains determined the class of hysteresis loops that can be obtained. For instance, it was illustrated that complex hysteresis loops with intersections whose sub-loops have the same orientation can exist.

In Chapter 4, we continued the study of the Preisach hysteresis operator, analyzing now the classic problem of absolute stability of Lur'e systems with a hysteretic nonlinearity in the feedback loop. Firstly, a relation between the input-output rate of the Preisach hysteresis operator was obtained. Later, assuming that the weighting function was compactly supported, we determined sector bounds for the input-output rate and use the classic circle criterion to prove the set stability of the closed-loop. The result was applied to Lur'e systems with Preisach butterfly non-linearity and Preisach multi-loop non-linearity

In Chapter 5, we addressed the study to the Duhem hysteresis operator. Firstly, we analyzed the accommodation property of the Duhem model, which roughly speaking corresponds to the convergence of its input-output phase plot to a periodic closed orbit when the input is periodic. We generalized the results of [4] and [22] in the sense that we imposed a reduced set of restrictions over the vector fields that compose the model to guarantee convergence of the input-output phase plot to a periodic loop when the input applied was periodic. In particular, neither sign-definiteness nor boundedness was required. Furthermore, based on this result, we introduced a class of Duhem models that exhibits butterfly hysteresis behavior.

In Chapter 6, we tackled a novel problem in hysteretic systems, which we denominated the remnant control problem. This problem surges as an opposite perspective to the dominant approach in literature where the presence of the hysteresis phenomenon is usually compensated or canceled. The remnant control problem is instead formulated to take advantage of the hysteresis memory effect to retain a particular system output or configuration without holding a control input. We presented in this chapter the formulation of the problem and a recursive control algorithm for ensuring convergence of the output remnant of the Preisach hysteresis operator and the Duhem hysteresis operator to a reference value.

Finally, in Chapter 7, we extended the results of the remnant control problem and presented a recursive control algorithm for the remnant of a novel conceptual platform denominated hysteretic deformable mirror (HDM). The HDM concept consists of a reflective top surface mounted on a stack of piezoelectric wafers with electrodes in-between. Using the remnant of every actuator, the whole platform aims to be controlled by a single control input which is time-multiplex for every one of the actuators. Nevertheless, due to the distribution and interconnection of the electrodes, it is expected that a coupling between the input of each actuator will occur. We presented a quasi-static modeling approach where every actuator of the HDM was composed of a Preisach hysteresis operator. Our recursive control algorithm exploited the congruency property of the hysteretic behavior to determine conditions such that the time-multiplexed input did not disturb the remnant of the actuators that already held their desired reference. Based on this principle, the convergence of the HDM to the desired mirror deflection was guaranteed.

8.2 Open Problems

Based on the results that have been presented in this thesis, we have identified a number of open problems that can be investigated for future research. These open problems are as follows.

- The construction of storage functions and characterization of properties such as dissipativity or passivity should be further explored for the butterfly and multi-loop hysteresis operators introduced in Chapters 3 and 5. In other words, for hysteresis operators whose input-output behavior is not always monotone and whose input-output phase plot can have intersections.

- The characterization of the classes of multi-loop hysteresis operators in Chapters 3 and 5 is not complete. It would be worthy to investigate if particular structures of weighting functions in the Preisach operator or certain gradient functions in the Duhem model guarantee the multi-loops hysteresis behavior.

- As it was investigated in Chapter 4 for the Preisach hysteresis operator, one should investigate also the absolute stability of Lur'e systems whose feedback non-linearity is described by a Duhem hysteresis operator that exhibits butterfly and multi-loop hysteresis behavior.

- For the recursive remnant control algorithms proposed in Chapters 6 and 7, modifications to increase the rate of convergence should be investigated. Furthermore, the remnant control problem for a Duhem hysteresis operator that exhibits butterfly or multi-loop hysteresis behavior can also be investigated.

- The experimental validity of the assumptions made in the quasi-static modeling approach presented in Chapter 7 for the HDM must be investigated.