Comparison of real-time control strategies with hysteresis compensation for magnetostrictive actuators

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Abstract. Magnetostrictive actuators are employed for several purposes but, often, the control strategy is strongly affected by their hysteretic behavior. Such issue becomes crucial if dynamic mechanical stress conditions apply. Indeed, the stress must be considered as an additional input. Nevertheless, a compensation scheme with two-input variables can be defined and fruitfully utilized in a suitable invertibility region. In this paper, different control strategies, based on a compensation algorithm able to take into account the applied mechanical stress, are proposed and compared with simpler linear controllers in a real-time setup. Experimental data measured over a magnetostrictive actuator are presented and commented.

Keywords: Magnetostriction, magnetostrictive devices, control systems, hysteresis, real-time experiments

1. Introduction

Magnetostrictive actuators can be employed in several tasks where both high forces and micrometric displacements are needed because the energy density of magnetostrictive materials is higher than the one of other smart materials like piezoelectrics [1]. Nevertheless, they show hysteresis between the deformation and the applied magnetic field. Moreover, the hysteretic characteristic depends on the mechanical load experienced by the actuator tip. Then, a magnetostrictive actuator should be modelled as a hysteretic two-inputs system and this model should be taken into account in the design of the closed loop controller.

Several models of two-inputs hysteresis have been presented in the past. Some of them have been conceived for magnetostrictive materials [2,3] but they are unsuitable for real-time control application, because of the heavy computation time and the cumbersome model identification procedure. Other models, more control-oriented, have shown promising results [4,5].

Closed loop control can be considered a necessary solution in presence of disturbances, model uncertainties or unstable processes to be controlled. In those cases the feedback allows to obtain performances otherwise unachievable by open loop (also said feedforward) solutions. However, the feedforward control has some important advantages with respect to the feedback control. For instance, it is easy to analyze control systems with feedforward controllers since the feedforward action (supposed to be implemented through a stable system) does not affect the stability of the overall control system and so its design is easier than the feedback control that, on the contrary, might make unstable a control system made of stable systems. Moreover the feedforward control is *faster* than the feedback control since its action (the input signal to the process) depends only on the feedforward controller dynamics and not also on the process dynamics. For these reasons modern control systems often employ both actions, through a feedforward and a feedback controller. Such a configuration is called two-degrees-of-freedom control system since in this way it is possible to design a controller that weights independently the reference signal and the measurements coming from the process [6,7]. Thus it is possible to obtain both the advantages of the two configurations overcoming, as far as possible, the trade-off intrinsically present in only one of the single approaches.

The methodology reported above can be applied for controlling nonlinear processes, as well, even though only few theoretical results dealing with nonlinear systems are available in the literature [8]. When the process presents a nonlinear behavior due to hysteretic phenomena, the problem is then more challenging. In particular it is not so straightforward to design the feedforward action in relation to the nonlinear process model. In this context some ideas have been recently proposed, by looking at hysteresis models and their inversion. Among several approaches, the Preisach model appears to be one of the most promising [9,10,11]. In [12] a two-degrees-of-freedom control system has been designed in order to control a piezoceramic actuator. The feedforward controller incorporates the inverse Preisach model of the actuator while the feedback controller is the cascade of a proportional-derivative and a lead-lag compensator. In [13] the inversion of the Preisach model is implemented in the feedback loop, instead, to control an electromagnetic actuator where hysteresis is due to soft ferromagnetic materials. Due to nonlinearity and model uncertainties and/or variations, the approaches are not equivalent in general and it is not easy to fully understand apriori what kind of performances can be expected.

In this paper we propose the experimental study of a recently proposed two-inputs compensator [10,11] that can be used in real-time control systems. The model is used to design different control strategies, including a two-degree-of-freedom control system.

2. Modelling and control of two-inputs magnetostrictive actuators with hysteresis

The characteristics of a magnetostrictive actuator show rate independent memory phenomena [14] with respect to the two-inputs [10], and therefore a generalization of the standard hysteresis operators, as the classical Preisach operator, is required [11]:

$$\varepsilon = \Gamma[f(H,\sigma)] + \lambda(\sigma) \tag{1}$$

where $\Gamma(\cdot)$ is a Preisach operator, $f(.,.)$ is a memoryless two-inputs function and $\lambda(\sigma)$ represents a pure elastic non linear behavior. This operator is able to fully model the device, including the internal state dependence from the mechanical stress [11]. A further feature of this approach is its identification process. In fact, the operator $\Gamma(\cdot)$ can be identified by a set of well defined experimental data (first order reversal curves) [14]. In the considered case it is identified at the constant mechanical load where the actuator shows its maximum stroke. Also the function $f(.,.)$ needs a limited set of data, made of single branches of the hysteretic limit cycles at constant mechanical loads. In a nutshell, it needs less identification data, with respect to other stress dependent models. Moreover, with suitable hypothesis on the involved functions and operators, it can be inverted with a low computational cost [15] still using the same identification data of the direct model and this makes it suitable for real-time control.

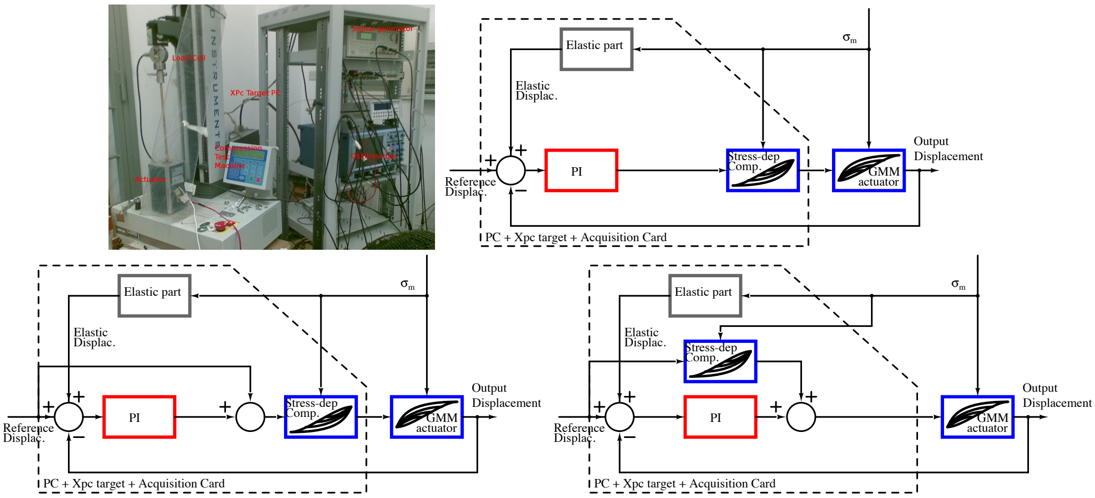

Fig. 1. Clockwise plots from left-up: experimental setup, control schemes A, B and C.

Once, the compensator is defined, it can be used in different control-schemes, ranging from the compensated open loop scheme to closed loops where the chain compensator-actuator can be approximated as a linear dynamic system, within the identification limits. Then, even simple Proportional-Integral (PI) controller can be used. The Fig.1 left-up shows the employed experimental setup: the compensation algorithms and the PI controller are implemented in a real-time environment, by means of a PC with Matlab and xPC Target toolbox and a 16 bit acquisition/generation card. The typical sampling time was about 20μs. The experimental setup includes a bipolar amplifier feeding the actuator in a current-controlled mode, an eddy current proximity sensor to measure the actuator displacement and a load cell to measure the dynamic load variations. The actuator is a custom unit with a Terfenol-D active element, preloaded with washer springs and biased with a permanent magnet. In this application, it has been driven up to ± 6 A with a maximum displacement of 135μm. The control schemes implementations are shown in Fig.1. Basically, they all share a feedback loop on the actuator displacement and an hysteresis compensator that takes into account also the measured stress (stress-dependent compensation). The three schemes differ in the compensator position and in the numbers of *degrees of freedom* of the control scheme. In particular,

- the scheme A is a one degree of freedom with only a feedback action aimed to regulate the desired actuator position. The stress-dependent compensator is placed before the actuator;
- the scheme B is a two degrees of freedom with a feedback loop and a feedforward action whose input is the desired position. In this case, the feedback loop is without compensation, while the stress-dependent compensator is placed in the feedforward action.
- the scheme C is a two degrees of freedom and, differently from scheme B, has both the feedforward action and the feedback loop with stress-dependent compensation.

Finally, it is worth noting that in the schemes A and C the compensator has the same internal state of the real actuator (within the modeling limits). This is not true for the scheme B because here the compensator input is only due to the desired displacement and does not take into account the real actuator output.

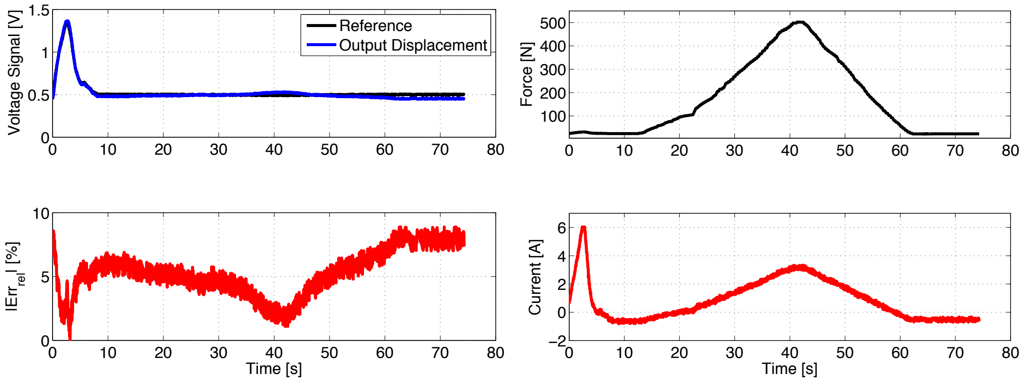

Fig. 2. Open loop test. Desired and measured displacements (left-up); displacement relative error (left-down); applied load (right-up); actuator driving current (right-down).

3. Experimental Results

A first test is reported considering an open loop control scheme, where the stress dependent compensator directly drives the actuator. This test can be considered as a representative motivation to employ an additional input, the stress in this case, in the control strategy. In particular, the desired and measured displacement are reported in Fig. 2 left-up. In Fig. 2 right-up the applied force variation is reported. By comparing those two figures there are temporal windows where the desired displacement is kept constant while the force varies. Instead, in the right-down plot the actuator driving current (computed by the stress dependent compensator) is reported. It is clear now the concept of the *effective* current: when the applied force is varying the compensation algorithm accordingly varies the driving current to hold the actuator displacement constant. From the error plot this strategy can be considered very effective.

In order to increase the control robustness with respect to parametric drifts or modeling errors a closed loop control strategy can be considered. In Fig. 3 a classic feedback control strategy with the stress compensator in the closed loop is tested by using a triangular displacement reference, varying the applied force in a wide range. As it can be seen lower tracking errors can be achieved with respect to the open loop case. In order to estimate the possible benefits of using a two-degree-of-freedom control system further tests are reported. In the Figs. 4,5,6 the classic closed loop strategy experimental results are compared with two other control strategies with feedforward actions.

In those measurements, the displacement reference is again a triangular waveform but with higher frequency and stress is varied back and forth the minimum and maximum allowable values. It can be noted that also the applied force influences the memory of the hysteretic actuator, as it is expected [15]. When a feedforward action is added, the reconstructing errors are lower suggesting that faster signals can be tracked, extending the benefits of the feed-forward action in terms of speed, as in the case of linear system control theory. In other words, it can be said that in the hypothesis of a perfect hysteresis compensation the presence of the feedforward action enhances the bandwidth of the feedback control scheme.

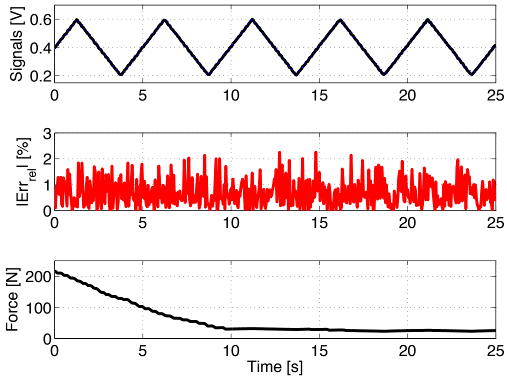

Fig. 3. Closed loop - scheme A, see Fig.1. Slow variation test.

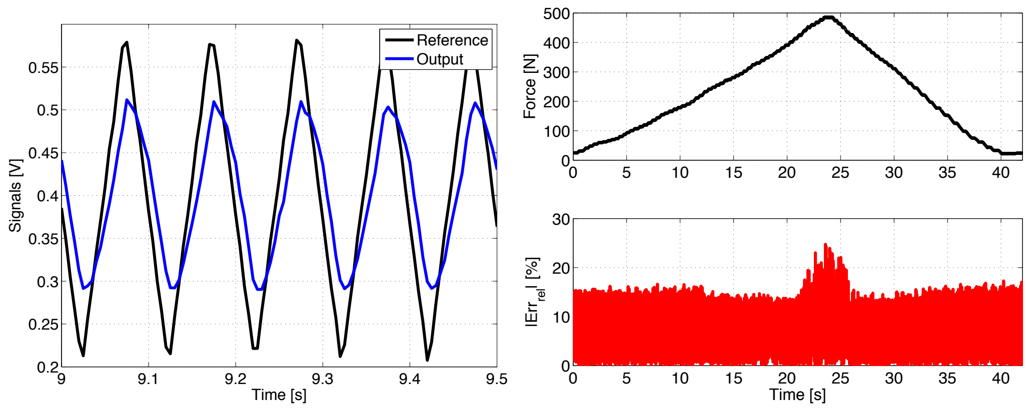

Fig. 4. Closed loop - scheme A, see Fig.1.

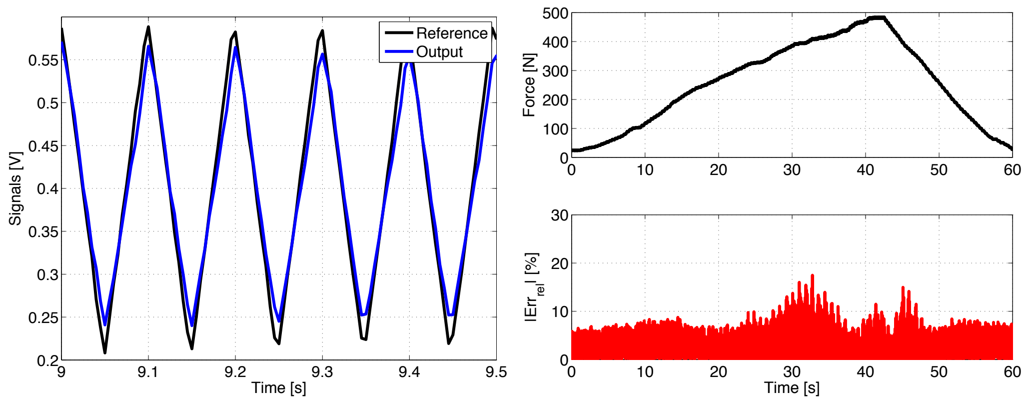

Fig. 5. Closed loop - scheme B, see Fig.1.

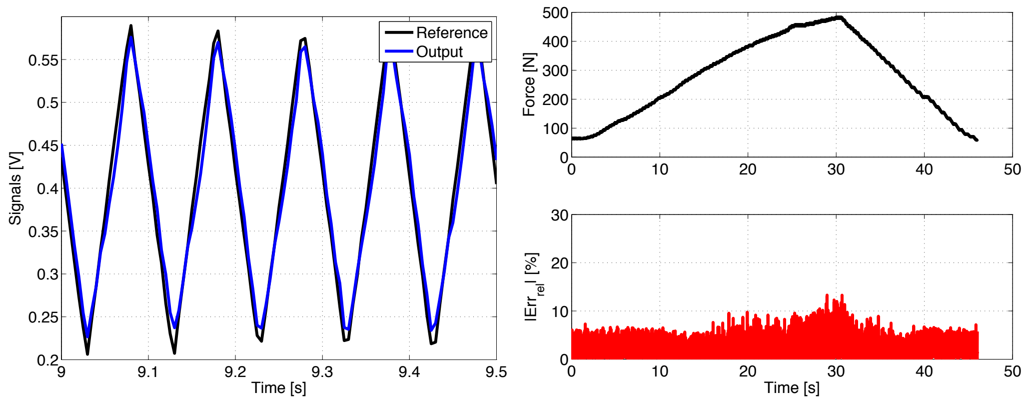

Fig. 6. Closed loop - scheme C, see Fig.1.

4. Conclusions

In this paper the effectiveness of using a two-input hysteresis compensator in a real-time environment has been demonstrated. Different control schemes have been tested by means of hardware in the loop experiments. Two-degrees-of-freedom control systems and feedback control strategies have been compared, highlighting their performances in the control of a magnetostrictive actuator. Moreover, it has been proved that combined feedforward-feedback actions can achieve better performances in terms of tracking error and speed of desired reference input signal also when a hysteretic actuator is employed.

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