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Simultaneous compensation of hysteresis and creep in a single piezoelectric actuator by open-loop control for quasi-static space active optics applications

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ABSTRACT

Owing to their excellent properties piezoelectric actuators are studied as embedded elements for the quasi-statically active shape control of spatial optical mirrors. However, unwanted nonlinear effects in piezoelectric actuators, i.e., hysteresis and creep, severely limit their performance. This paper aims at developing a control methodology to compensate hysteresis and creep in a piezoelectric actuator simultaneously for quasi-static space active applications. In the methodology developed, hysteresis and creep behaviors are successively compensated by open-loop control. First, a derivative Preisach model is proposed to accurately portray the hysteresis while requiring relatively few measurements and describing the detachment between major and minor loops. The inverse derivative Preisach model is derived and inserted in open-loop to achieve hysteresis compensation. Then, the creep in the hysteresis compensated piezoelectric actuator is described by the use of a nonlinear viscoelastic model and a low pass filter is suggested to eliminate the effect of the inverse derivative Preisach model on the step reference input. To invert the creep model, the concept of "input relaxation" is implemented and an inverse multiplicative structure allows identifying the parameters of the inverse model while circumventing the difficulty of a mathematical computation. Finally, by cascading the low pass filter, the inverse model of creep and the inverse derivative Preisach model one after the other with the single piezoelectric actuator, the simultaneous compensation of hysteresis and creep is achieved. Experimental results show that in the case of step-like reference signals the hysteresis and the creep in a piezoelectric actuator can be significantly reduced at the same time. It implies that the developed methodology is effective and feasible in space active optics applications for which quasi-static distortions need to be compensated.

1. Introduction

This paper concerns the shape control of active optical systems of space telescopes to correct wave-front errors induced by on-orbit environment and more particularly the correction of wave-front errors induced by thermal gradient. Indeed, with their high resolution, fast response, high stiffness, and no backlash or friction, piezoelectric actuators attract attention for the design of space telescopes. Recently piezoelectric actuators have found new applications in the active optical systems of space telescopes (ex. James Webb Space Telescope, 2010). However, despite their many advantages, piezoelectric actuators exhibit unwanted nonlinear effects such as hysteresis and creep—which may lead to undesirable inaccuracy and limit service performance (Leang & Devasia, 2002; Wang, Budinger, & Gourinat, 2013). Hysteresis, which is observed between the voltages applied to the actuator and the obtained displacement as seen in Fig. 1, is a nonlinearity which comes from the dependence of the piezoelectric actuator not only on its current input voltages but also on the past voltages. In the case of dynamic applications, the rate-dependence of the hysteresis in piezoelectric materials (dependence on the frequency of the input signal) must be taken into account. Hysteresis severely limits system performance, since it leads to a positioning uncertainty of up to 15% of motion range (Moriyqmq, Uchida, & Seya, 1988). Creep, a slow drift of the piezoelectric actuator displacement responding to a constant input as shown in Fig. 2 (Osamah, Rifai, & Youcef-Toumi, 2002), is the effect of the remnant

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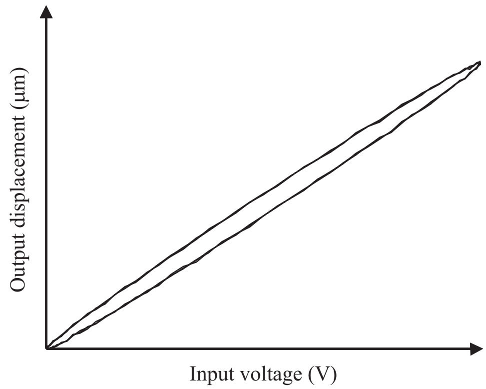

Fig. 1. Hysteresis in piezoelectric actuator.

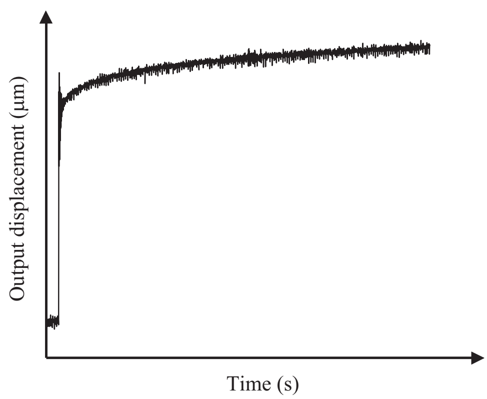

Fig. 2. Creep in piezoelectric actuator.

polarization which continues to change over time (Minase, Lu, & Cazzolato, 2010). Creep can cause unaffordable positioning errors in quasi-static applications (Lee, Lee, & Kim, 2008).

To compensate for hysteresis and creep in piezoelectric actuators, closed-loop control techniques seem to be the best way to improve positioning precision and provide robustness to model uncertainties and parameter variations (Crews, McMahan, Smith, & Hannen, 2013; Fleming & Leang, 2010; Guo & Zhu, 2010; Kuhnen & Krejci, 2009; Leang & Devasia, 2002). However, owing to the high cost and space requirements of displacement sensors, in practice the use of closed-loop control techniques can be limited, especially in the case of large deformable mirrors for which the number of actuators may be high (a few hundred in some applications (Cornelissen, Hartzell, Stewart, Bifano, & Bierden, 2010; Madec, 2012)). An alternative way to minimize hysteresis and creep is to use charge input instead of voltage input to drive the piezoelectric actuators (Clayton, Tien, Fleming, Moheimani, & Devasia, 2008; Fleming, 2013; Goldfarb & Celanovic, 1997; Minase et al., 2010). Charge control can significantly reduce the effects of hysteresis and creep, but at the expense of reducing the effective displacement range of the actuator (Leang & Devasia, 2002) and of increasing the electronic complexity required for the effective charge control (Minase et al., 2010). Hence, the open-loop control techniques attract considerable attention. These techniques are based on the models of hysteresis and creep and compensate their effects with feed-forward controllers.

With respect to hysteresis, many works have been performed. Many of them have been reviewed in (Hassani, Tjahjowidodo, & Nho Do, in press) in the general case and in (Ge & Jouaneh, 1995) for piezoelectric actuators more particularly. Some works concern only hysteresis modeling techniques, others go further and propose models and their use in a feedforward control scheme.

To model hysteresis, the Preisach (Ge & Jouaneh, 1997; Visintin, 1994) and Prandtl–Ishlinskii (PI) (Janaideh, Mao, & Rakheja, 2008; Sining & Chun-Yi, 2011) models that belong to the class of operator-based models are very popular. The Preisach model is expressed with a double integrator in a continuous form or in a simpler manner with α–β triangles in a numerical form. A modified Preisach model using finer mesh triangles is proposed in (Raghavan, Seshu, & Gandhi, 2003) to model the hysteresis more accurately. In Park and Washington (2004) and Yang, Li, Wang, Ye, and Su (2009), a neural network is used with the Preisach model to improve the accuracy. Because of its accuracy and the simplicity of its implementation, the Preisach model is widely used for the modeling of hysteresis in piezoelectric material despite one disadvantage: the Preisach model is basically rate-independent although the hysteresis in piezoelectric materials is rate-dependent. To make the model rate-dependent, Dang and Tan (2005) use hysteresis operator of first-order differential equation and Xiao and Li (2013) the Fast Fourier Transform to approximate the density function. The PI model is a subset of the Preisach model with 2 operators called stop and play which are simpler than the operators of the Preisach model but inherit the centrally symmetric property of play operator which can only describe the symmetric hysteresis. Modifications to the classical PI model are needed to model asymmetric hysteresis (Al Janaideh, Su, & Rakehja, 2008; Dong, Zaili, Niandong, & Shuai, 2011). The classical PI model is also rate-independent and different PI models are proposed in Al Janaideh, Rakheja, and Su (2008) and Al Janaideh, Rakheja, and Su, (2009) to overcome this drawback. The classical PI model is also acclaimed for its simplicity of implementation. Like the Preisach model, the construction of the PI model, even if feasible, is not always done easily. Another class of models is the class of differential-based models. Among these models are the Bouc–Wen model and the Duhem model. The Bouc–Wen model is expressed by means of a nonlinear differential equation. It is basically a rate-independent model and it must be formulated with a linear Hammerstein model to take into account the rate-dependency (Zhenyan, Zhen, Jianqin, & Kemin, 2012). The Duhem model (Ru, Chen, & Shao, 2009) is expressed as a set of nonlinear differential equations and is presented in a more complex way than the Bouc–Wen model. It is also a rate-independent model. In the work of Yeh, Hung, and Lu (2008), the model utilizes a parallel connection of Maxwell-slip elements and a nonlinear spring to describe hysteresis and a dynamic damper is incorporated to account for the frequency-dependent hysteresis behavior. All these models are phenomenological models concerned with accurately modeling the hysteretic response without quantifying the physics responsible for the behavior. Some models like homogenized energy model (HEM) quantify the hysteretic behavior with a perspective to incorporate underlying physics (McMahan, Crews & Smith, 2013)).

Regarding to the use of the hysteresis models for control purpose, the Bouc–Wen model is not invertible, it requires the use of an inverse multiplicative structure (Rakotondrabe, 2011) or of a Bouc–Wen least square support vector machine to identify and compensate hysteresis in feedforward control without the need of an inverse model (Xu, 2013). The Duhem model is difficult to invert because of its structure as a differential-based model. Both models are more adapted to feedback control strategy (Feng, Rabbath, Chai, & Su, 2009). The Preisach and (PI) models have been widely used for control, in both configurations of feedforward or feedback schemes (Ang, Khosla, & Riviere, 2007; Al Janaideh, Feng, Rakheja, Su, & Rabbath, 2009; Gorbet & Morris, 2003; Li, Su, & Chai, 2014; Song, Zhao, Zhou, & De Abreu-García, 2005; Weibel, Michellod, Mullhaupt, & Gillet, 2008).

With respect to creep, many models have been developed to characterize creep behavior, the most common being the LTI