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Linear Active Disturbance Rejection Control for Nanopositioning System

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ABSTRACT

Nanopositioning systems have wide range of applications. It usually takes piezoelectric as a driver. However, the inherent hysteresis of piezoelectric actuators not only reduces the accuracy of the system, but also may make a system be unstable. In order to eliminate hysteresis nonlinearity, active disturbance rejection control (ADRC) is utilized. Hysteresis nonlinearity is considered as disturbance, and ADRC is designed to estimate and eliminate its effect so as to improve the control accuracy. Considering the unavoidable measurement noise, we extend a dimension of extended state observer. As a consequence, a modified linear ADRC (LADRC), whose performance is better than LADRC, is obtained. The experimental results prove that the proposed approach is feasible and effective.

1. Introduction

Nano-positioning technology is crucial technology in modern science and engineering applications, such as atomic force microscope, scanning tunneling microscope, biological microscope surgery, biological nano-technology, nano-assembly etc (Xu 2017). Piezoelectric actuators with high resolution, small size, large output force, high frequency, low heat generation and fast response are always the first choice in nano-positioning systems (Wei et al. 2016). The inherent hysteresis nonlinearity of piezoelectric actuators, however, definitely reduces system accuracy, or even results in instability of a system. Therefore, it has become the current hot spot that how to eliminate the hysteresis nonlinearity in a closed-loop nano-positioning system.

To overcome the adverse effect of hysteresis, much efforts have been made and a variety of control methods have been put forward. The reported approaches can be classified into feedforward control, feedback control and feedforward-feedback control (Gu et al. 2016). In general, inverse hysteresis model is taken in feedforward control so as to compensate the undesired hysteresis (Gu & Zhu 2014, Iyer & Tan 2009). However, such methods depend much on hysteresis or inverse hysteresis model. It is difficult and costly to get a faithful hysteresis model. Meanwhile, the existence of the inverse model and the complexity of the system will also affect the system performance.

For the purpose of improving the accuracy of positioning, feedback control technology have always been utilized to address the nonlinearities, uncertainties and un-modeled dynamics. As a matter of fact, a feedback closed-loop control system with hysteresis nonlinearity is a challenge. Since hysteresis is always unknown, and it may result in instability of a closed-loop system, PID and many modified PID controllers (Polit & Dong 2011, Tan et al. 2001) have been designed in nanopositioning. However, generally, PID control can be utilized in relatively low frequencies cases or under a small travel range due to the limitations on tracking bandwidth and ability to deal with hysteresis in trajectory tracking. To address those limitations, repetitive control (Li et al. 2017), sliding mode control (Xu 2017), and H_∞ control (Rakotondrabe, 2009) have been designed to improve the positioning performance in presence of model uncertainties and hysteresis nonlinearity.

The combination of feedforward and feedback control is another choice to enhance the tracking performance (Shan & Leang 2012, Gu et al. 2014, Cao et al. 2013). In general, feedforward controller is designed to compensate hysteresis, and feedback controller is developed to eliminate the uncompensated hysteresis, unmodeled dynamics, and system uncertainties. Additionally, there is another structure of feedforward-feedback control. The feedforward controller is obtained on the basis of the closed-loop inversion. Comparisons of such two feedforward and feedback control schemes have been discussed (Butterworth 2009).

Different kinds of control approaches have been proposed for the nanopositioning control. However, feedforward control depends much on the model or the inverse model of hysteresis. Feedback control, on the other hand, is activated when system output is different from the desired tracking signal. It is a passive approach to

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make the system output tracks the reference signal.

Active disturbance rejection control (ADRC), proposed by Han, is the very technique to actively deal with uncertainties (Han 2009). From the point of ADRC, the cascade of integrators is the standard form for any system. Discrepancy between system dynamics and the standard dynamics is viewed as the generalized disturbance. Extended state observer (ESO) estimates system states and the generalized disturbance. System output can be guaranteed by compensating the generalized disturbance before it affects system performance. However, parameters of ADRC are difficult to be obtained. Linear active disturbance rejection control (LADRC) has been proposed (Gao 2003), and there are just two tunable parameters. LADRC inherits desired performance of ADRC, but it is more acceptable to engineers. Numerous applications of ADRC/LADRC can be found in different fields (Yang et al. 2017, Zhang & Chen. 2016, Tao et al, 2017, Xia et al. 2016).

Nevertheless, system output is always corrupted by sensor noise. In order to improve the tracking performance of LADRC, a low-pass filter is introduced so as to enhance the ability of ESO. Experimental results are presented to confirm the proposed approach.

2. Linear active disturbance rejection control

Consider a second order system

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(\cdot) + b_0 u \\ y = x_1 \end{cases} \tag{1}$$

where x_1, x_2 are system states, $f(\cdot)$ is the generalized disturbance, y is the system output, u is the system control input, b_0 is the coefficient of control input.

Control law u is designed as

$$u = \frac{k_p(y_r - z_1) - k_d z_2 - z_3}{b_0} \tag{2}$$

where k_p, k_d are tunable control parameters, y_r is the desired output, z_1, z_2, z_3 are states of linear ESO (LESO), whose dynamics is

$$\begin{cases} \dot{z}_1 = z_2 + \beta_1 e \\ \dot{z}_2 = z_3 + \beta_2 e + b_0 u \\ \dot{z}_3 = \beta_3 e \end{cases} \tag{3}$$

where $e = y - z_1$ is the estimation error, $\beta_1, \beta_2, \beta_3$ are tunable parameters of ESO.

Second order LADRC structure is shown in Fig. 1

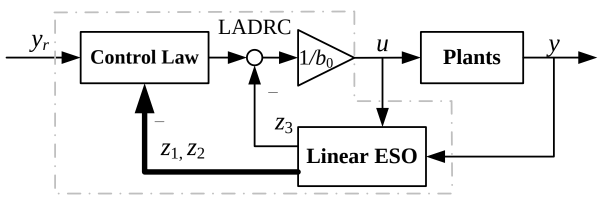


Fig. 1. Structure of second order LADRC

According to system (1) and LESO (3), we have

$$e^{(3)} + \beta_1 \ddot{e} + \beta_2 \dot{e} + \beta_3 e = \dot{f}(\cdot) \tag{4}$$

For a practical system, the generalized disturbance $f(\cdot)$ is always bounded. If $\beta_1, \beta_2, \beta_3$ are chosen properly, LESO is convergent. However, measurement noise always exists, i.e. system (3) can be depicted as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(\cdot) + b_0 u \\ y = x_1 + n \end{cases} \tag{5}$$

where n is the measurement noise. System structure can be shown in Fig. 2.

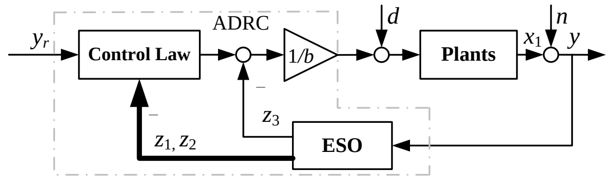


Fig. 2. Structure of second order ADRC with sensor noise

Then estimation error can be written as

$$\varepsilon = y - z_1 = x_1 + n - z_1 = e + n$$

Hence, we have

$$\varepsilon^{(3)} + \beta_1 \ddot{e} + \beta_2 \dot{e} + \beta_3 e = \dot{f}(\cdot) + n^{(3)} - \beta_1 \ddot{n} - \beta_2 \dot{n} - \beta_3 n \tag{6}$$

From (6), we can see clearly that sensor noise can affect the estimation error with the help of the gain of ESO. Measurement noise does reduce the performance, or even make the closed-loop be unstable.

3. Modified linear disturbance rejection control

In practice, a more purified system output is in great need. Here, a low-filter is introduced in LESO, i.e.

$$\begin{cases} \dot{z}_0 = (y - z_0)/\tau \\ \dot{z}_1 = z_2 + \beta_1 e_l \\ \dot{z}_2 = z_3 + \beta_2 e_l + bu \\ \dot{z}_3 = \beta_3 e_l \end{cases} \tag{7}$$

where y is the system output including sensor noise, z_0 is the system output after filtering, τ is the tunable parameters, and e_l is the estimation error between system (5) and (7).

Control law is also the same as (2).

4. Experimental results

4.1 Experimental setup

A nanopositioning stage is designed and modified LADRC is programmed in Turbo programmable multi-axis controller (PMAC). The stage is shown in Fig. 3.

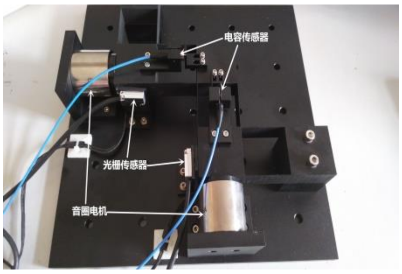
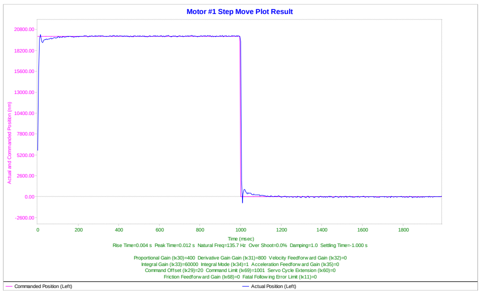


Fig. 3. Experimental setup of a nanopositioning stage

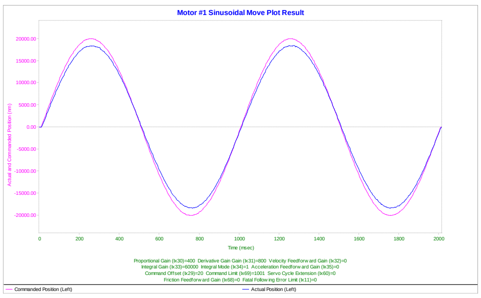
Experiments have been performed. Both PID and modified LADRC have been realized. Step signal, sinusoidal signal, and sawtooth signal have been assigned as the reference signals, respectively. Parameters of PID and modified LADRC are given in Tab. 1. Tracking performance have been compared.

Tab. 1. Parameters of PID and modified LADRC

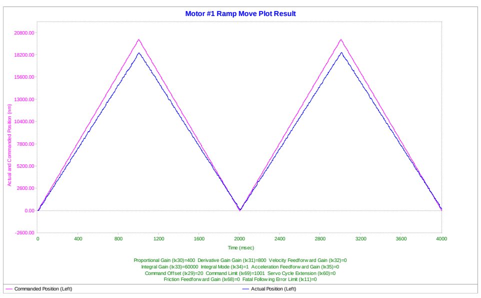
Parameters	K_p / b_0	K_i / ω_c	K_d / ω_o	τ
PID	400	6e4	800	-
Modified LADRC	2e5	200	1000	0.01



(a)

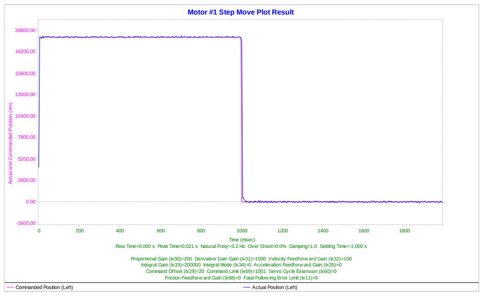


(b)

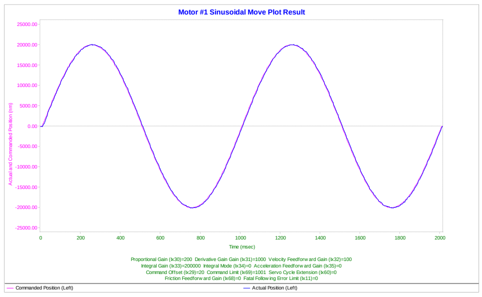


(c)

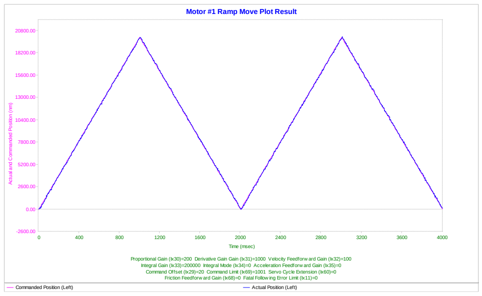
Fig. 4. Tracking performance of PID



(a)



(b)



(c)

Fig. 5. Tracking performance of modified LADRC

From the experimental results, we can see clearly that moidified LADRC is superior to PID. It confirms that ESO is able to estimate the generalized disturbance effectively and the estimated disturbance can be compensated in the control channel in time.

5. Conclusion

The measurement noise will damage the system output signal, which may greatly affect the overall system performance. In this paper, measurement noise is taken into consideration, and a modified LADRC is proposed. The performance of the proposed approach is confirmed by the comparison with PID. However, it is the preliminary results, further work is on the way.

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References

C. X. Li, G. Y. Gu, M. J. Yang, et al., 2017, High-Speed tracking of a nanopositioning stage using modified repetitive control, IEEE Trans. Automation Science and Engineering, 14(3), 1467-1477.

C. Y. Zhang, Y. L. Chen, 2016, Tracking control of ball screw drives using ADRC and quivalent-error-model-based feedforward control, IEEE Transactions on Industrial Electronics, 63(12), 7682-7692.

G.-Y. Gu, L.-M. Zhu, C.-Y. Su, H. Ding, and S. Fatikow, 2016, Modeling and control of piezo-actuated nanopositioning stages: A survey. IEEE Trans. Autom. Sci. Eng., 13(1), 313–332.

G. Y. Gu and L. M. Zhu, 2014, Comparative experiments regarding approaches to feedforward hysteresis compensation for piezoceramic actuators, Smart Mater. Structures, 23(9), 0950291-09502911

G. Y. Gu, L. M. Zhu, and C. Y. Su, 2014, High-precision control of piezoelectric nanopositioning stages using hysteresis compensator and disturbance observer, Smart Mater. Structures, 23(10), 1050071-10500710.

J. A. Butterworth, L. Y. Pao, and D. Y. Abramovitch, 2009, A comparison of control architectures for atomic force microscopes, Asian J. Control, 11(2), 175-181.

J. Han, 2009, From PID to active disturbance rejection control, IEEE Transactions on Industrial Electronics, 56(3), 900-906.

J. Tao, Q. L. Sun, H. Sun, et al., 2017, Dynamic modeling and trajectory tracking control of parafoil system in wind environments, IEEE/ASME Transactions on Mechatronics, 22(6), 2736-2745.

K. K. Tan, T. H. Lee, and H. X. Zhou, 2001, Micro-positioning of linear piezoelectric motors based on a learning nonlinear PID controller, IEEE/ASME Trans. Mechatronics, 6(4), 428-436.

M. Rakotondrabe, Y. Haddab, and P. Lutz, 2009, Quadrilateral modeling and robust control of a nonlinear piezoelectric cantilever, IEEE Trans. Control Syst. Technol., 17(3), 528–539.

N. F. Yang, F. Gao, D. Paire, et al., 2017, Distributed control of multi-time scale DC microgrid based on ADRC, IET Power Electronics, 10(3), 329-337.

Qingsong Xu, 2017. Continuous Integral Terminal Third-Order Sliding Mode Motion Control for Piezoelectric Nanopositioning System. IEEE/ASME Trans. On Mechatronics, 22(4), 1828-1838.

R. V. Iyer and X. Tan, 2009, Control of hysteretic systems through inverse compensation, IEEE Controls Syst. Mag., 29(1), 83-99.

S. Polit and J. Dong, 2011, Development of a high-bandwidth XY nanopositioning stage for high-rate micro-/nanomanufacturing, IEEE/ASME Trans. Mechatronics, 16(4), 724-733.

Wei W., Donghai Li, Min Zuo, Zaiwen Liu, 2016, Active disturbance rejection control design for piezoelectric positioning system, Control Theory and Applications, 33(10): 1319-1326.(In Chinese)

Y. Cao, L. Cheng, X. B. Chen, and J. Y. Peng, 2013, An inversion-based model predictive control with an integral-of-error state variable for piezoelectric actuators, IEEE/ASME Trans.Mechatronics, 18(3), 895-904.

Y. Shan and K. K. Leang, 2012, Accounting for hysteresis in repetitive control design: Nanopositioning example, Automatica, 48(4), 1751–1758.

Y. Q. Xia, F. Pu, S. F. Li, Y. Gao, 2016, Lateral path tracking control of autonomous land vehicle based on ADRC and differential flatness, IEEE Transactions on Industrial Electronics, 63(5), 3091-3099.

Z. Q. Gao, 2003, Scaling and bandwidth-parameterization based controller tuning, Proceedings of the American Control Conference, 4989-4996.

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