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A novel levitation control strategy for a class of redundant actuation maglev system

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ABSTRACT

In most maglev (magnetic levitation) systems, redundant electromagnetic actuators are usually used to increase the stability and robustness of the levitation motion. However, the obvious interactions generate between the redundant actuators and other general electromagnetic actuators. In this paper, a new and efficient redundant levitation control strategy is developed to overcome the interactions in this maglev system. In the strategy, some separate general controllers are designed for all general actuators, and then some special controllers are used to real-time track the electromagnetic forces of all general actuators, and accordingly they create control signal for the redundant actuators to counteract the interactions among general actuators and redundant actuators. To further illustrate the strategy, a novel redundant actuation maglev system is then demonstrated, and a simplified expression of the redundant control strategy is investigated for the maglev system. The experimental results show that the redundant levitation controller successfully removes the interactions between redundant actuator and general actuators, and the redundant levitation controller maintains good robustness under disturbance.

1. Introduction

Magnetic levitation is a contact-free and wear-free technology. Due to its excellent superiority over traditional moving mechanisms, maglev technology has been used in various fields such as high-speed maglev trains, frictionless bearings and ultra-precision motion platforms (Chen, Wang, & Fu, 2003a; Cole, Keogh, Sahinkaya, & Burrows, 2004; Fulford, Maggiore, & Apkarian, 2009; Luo, Chen, Ahn, & Pi, 2010; Shan, Kuo, Zhang, & Menq, 2002; Shi, Zmood, & Qin, 2004; Wai & Lee, 2008). As an alternative to traditional mechanically driven positioning systems, ultra-precision maglev motion platforms with many degree-of-freedoms (DOFs) have drawn more and more attention in recent years (Chen, Wang, & Fu, 2003b; Kim, Lee, & Han, 2003; Zhang & Menq, 2007). However, to steadily levitate the moving platform over the stator and realize ultra-precision motion in many maglev positioning systems, more electromagnetic actuators are usually used than those of the controlled DOFs. For instance, a linear maglev transportation system uses four electromagnetic actuators to control three DOFs for providing vertically suspension motion (Wai & Lee, 2008); an ultra-precision maglev positioning stage employs ten actuators to control six DOFs for realizing multiple DOFs motion (Shan et al., 2002); and six electromagnetic actuators are used to control five DOFs in a linear magnetic bearing (Kim et al., 2003).

Fig. 1 demonstrates a nominal moving platform of such a typical redundant actuation maglev stage. Without loss of generality, it is assumed that the platform is in a cubic shape and the center of mass is located at the origin of Cartesian coordinates $[X\ \ Y\ \ Z]$. Six electromagnetic actuators (i.e., electromagnetic actuators 1, 2, 3, 4, 5 and 6) are fixed at points A_1, A_2, A_3, A_4, A_5 and A_6. They are employed to generate electromagnetic forces f_1, f_2, f_3, f_4, f_5 and f_6, indicating that six electromagnetic forces are used to control five DOFs of the platform (i.e., linear motion y and z along the axes Y and Z, rotation motions α, β and γ around axes X, Y and Z). The linear motion x along the axis X is usually implemented by linear motor. Assume Z' is the cross point of the axis Z and the upper surface. Theoretically, when Z' is in or on the triangular boundary formed by points A_1, A_2 and A_3 (i.e., the shaded triangular area in Fig. 1), the platform can be stably supported by only three polings without any coupling among these three supporters. To increase the robustness of high-speed and ultra-precision motion, a redundant but not unwanted supporter (i.e., f_4) is usually included. Just like the four wheels of a car, they are symmetrically installed on both sides of the car and make the driving possess better bearing capacity and robustness. In order to distinguish four actuators, the actuators creating

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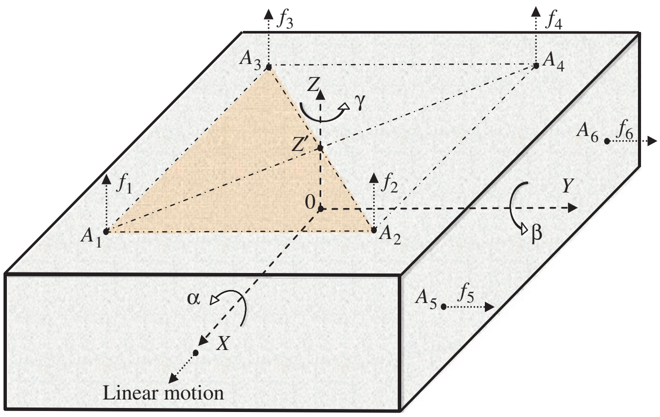

Fig. 1. Sketch of a nominal moving platform.

f_1, f_2 and f_3 are called general actuators, and the actuator creating f_4 is called redundant one in this paper.

The inclusion of redundant actuator would create greater stability and support force to the moving platform, but it also causes obvious coupling effects to the existing three supporters undoubtedly. It is difficult to give a proper description of the coupling relationship in simple words. But a qualitative notion can be achieved by comparing the cases with and without redundant actuator. When only f_1, f_2 and f_3 are used to support the platform, the change of any force has no impact on the other two. For instance, if f_1 increases or decreases, the position of A_1 along the axis Z will increase or decrease, while positions of A_2 and A_3 will not be influenced. When the redundant actuator is included (i.e., f_1, f_2, f_3 and f_4 are used to support the platform), the change of any force will influence at least the other two forces. It means that when f_1 increases or decreases, the position of A_1 along the axis Z will accordingly increase or decrease, while position of A_4 may not be influenced, but position of A_2 and A_3 will accordingly be increased or decreased. The position fluctuations of A_2 and A_3 will result in the change of f_2 and f_3 (because in magnetic suspension, the suspension force depends on the suspension position), thereby causing new fluctuations of all four suspension forces. Moreover, the strong nonlinear characteristics of maglev system strengthen the interactions, and if the actuator is not an electromagnet, the coupling effects may be not so obvious. As a proof, an experiment is conducted to quantificationally analyze these interactions and the consequences in the subsequent experiment part (i.e., Section 4.1).

Continuing the example of the nominal platform in Fig. 1, the system inputs are $u_{7\times 1} = [i_1\ i_2\ i_3\ i_4\ i_5\ i_6\ i_7]^T$, where current $i_1 \sim i_6$ are for six electromagnets and i_7 is for linear motor, while the system outputs are $\underline{y} = [x\ y\ z\ \alpha\ \beta\ \gamma]^T$. However, there are many difficulties in controlling such a Seven-Input Six-Output redundant actuation maglev system. The biggest one is the strong interactions between redundant actuator and general ones. Additionally, many inherent nonlinear characteristics in maglev system will increase its redundant control difficulties. For example, (i) the electromagnet has many inner strong nonlinear characteristics, i.e., hysteresis, magnetism saturation and parameter variation and (ii) the maglev system is a typical open-loop unstable system and its equilibrium region is severely restricted (da Rocha, Ferreira, Porsch, & Sales, 2009; Lee, Sung, Lim, & Bien, 2000). Therefore, the effective removal of the obvious interactions has become a very important precondition for achieving high performance levitation control, especially when the suspension precision is highly required, and the redundant levitation control needs to be solved more urgently. Nowadays, research on redundant maglev control has attracted much more attention. However, most literatures just treated the redundant actuation levitation system as general Multi-Input Multi-Output (MIMO) system and smoothed the strong interaction effects with intelligent methodology (Chen et al., 2003a; Fulford et al., 2009; Shan et al., 2002; Wai & Lee, 2008). The control strategy is as follows: the Seven-Input Six-Output redundant actuation maglev system is firstly transferred into a general Six-Input Six-Output system with $u_{7\times 1} = M_{7\times 6} \times u^*_{6\times 1}$ by adopting a nominal control effect $u^*_{6\times 1}$ and a transition matrix $M_{7\times 6}$; then many control techniques are employed to control the converted MIMO maglev system, such as adaptive control in Kuo, Shan, and Menq (2003) and Shan and Menq (2002), neural network in Wai and Lee (2009) and robust control in Shan et al. (2002). It is incontestable that the above controllers have achieved good control performance. But it is also worthwhile noting that the control performance mainly depends on the parameters updating of the adaptive tracking controllers. As is well known, for a nonlinear MIMO coupling system with p channels (e.g., p inputs and p outputs), the jth ($1 \le j \le p$) output will be caused by not only the jth input but also all other inputs. Meanwhile, the parameter updating of jth channel also influences all other channels. The interdependent relationship between channels will inevitably degrade their control performance. Although the intelligent adaptive controllers can finally maintain good tracking performance for every channel after longtime controller parameter adjustment (Li & Tong, 2003), longtime controller adaptation will degrade the control performance for the systems affected by nonlinear time-varying uncertainties, especially when the system dimension is high. On the other hand, the transition matrix $M_{7\times 6}$ is a constant, which will not change with any time-varying factor of the nonlinear system. Therefore, it is a key topic to make each input only affect its corresponding output separately for redundant maglev systems (Dai, He, Zhang, & Zhang, 2001).

A good redundant controller should work as follows: all the inter-channel connections are disconnected and each channel work independently. Moreover, the redundant controller should be simple, effective and easy to be implemented. In this paper, a novel redundant levitation control strategy is proposed for this class of redundant actuation maglev system. In the strategy, separate controller is designed for every channel. In the separate controllers, one special controller is used to real-time track the electromagnetic forces of all general actuators, and accordingly create control signal for the redundant actuator to counteract the interactions among general actuators and redundant actuator. The experimental results show that the redundant control method realized good decoupling control performance. This control strategy also shows other advantages. (1) In centralized control, one controller is used to control all four actuators, and any tiny change of any controller parameter will affect all channels' output. The controller is large and complicated, and it is unavailable for practical control. But for the present decentralized control, one controller serves one channel, and the general traditional and intelligent control techniques that are well-suited for single-input single-output (SISO) problems, such as PID, Fuzzy, Neural Network and Robust Control, can be adopted here. (2) For the moving platform in industrial application, the motion goals are often changed along with work tasks. The decentralized control strategy facilitates the adjustment of the motion goals of any channel at any times. For instance, when it is necessary to increase or decrease the levitation position of electromagnet actuator 3, one just needs to adjust its corresponding controller to smooth the fluctuation caused by levitation position change, and does not have to readjust all controllers. (3) The decentralized control does not increase the cost of controller design and manufacture compared with that of centralized control, though the number of controllers is larger than 1.