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Investigation on an integrated approach to modelling and analysis of multi-axis aerostatic bearing stages for high precision performance

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Abstract
Multi-axis aerostatic bearing stages are one of key enabling element units for precision and ultra-precision machines. These stages are essentially important for high precision positioning of the tool and/or workpiece and their dynamic and static actuation, while their higher and more robust dynamic performance is increasingly demanded.
In this paper, an integrated modelling and analysis approach is presented for the multi-axis aerostatic bearing stages system. The approach is focused on addressing two folds of challenges, i.e. the integrated analysis of mechanical design, electric drive actuation through the advanced cross-coupling-controller with variable gains for a direct drive aerostatic bearing linear stages as a complete high precision mechatronic system, and the simultaneous tuning and further analysis of the multi-axis aerostatic bearing stage system through PID control algorithms. It thus aims to achieve the higher positioning accuracy, response time and stability of the stage motions, especially during the high-speed multi-axis synchronized actuations in a precision engineering application. The modelling and analysis are implemented in MATLAB/Simulink environment and further supported by advanced control functions particularly for coupling, tuning and dynamic performance analysis. The paper is concluded with a further discussion on the potential and application of the approach for high precision multi-axis stages.

Keywords: aerostatic bearing, high precision multi-axis stages, integrated modelling and analysis, cross-coupling control, high precision mechatronics.

1. Introduction

Over the past three decades or so, aerostatic bearing direct drive stages have been gaining increasingly wide applications because of their nanometric positioning accuracy, extremely high dynamic performance, almost zero friction and unique environment-friendly characteristics. They are becoming the key indispensable building component for modern advanced machines and utilized in various precision engineering applications, such as ultraprecision machine tools, metrology instruments and equipment, the XY platform for high-precision 3D printing, and the positioning/actuation system for micromachining purposes, etc [1]. Therefore, the design, simulation and commissioning of drive and control systems for aerostatic bearing direct drive stages have received increasing R&D attention, as they directly affect the accuracy and dynamic performance of the stage systems. However, for most precision machines, their motion/positioning systems are often composed of multi-axis slideways or stages while individual single-axis slideway being tuned and commissioned during manufacturing, which often produces unexpected errors when multi-axis slideways work together simultaneously in the complex multi-axis CNC working environment. Therefore, with the increasing demands for higher precision of multi-axis machines, the development of a multi-axis cross-coupling control and the corresponding advanced control algorithms is essentially needed to realize integrated tuning of the multi-axis motion system, especially for rapid modular reconfiguration of multi-axis slideways/stages at a high precision machine. In addition, the cross-coupling control method can help compensate for contouring errors based on the feedback of actual tracking errors and thus further improving the motion and positioning accuracy particularly in machining complex freeform surfaces.

Koren firstly introduced the biaxial control strategy in 1980s [2] and further developed the cross-coupling-control method in early 1990s [3]. However, most of the early research and development related work for cross-coupling control was applied to the control of conventional CNC machines with servo-motor-driven ball screw-lead slideways/stages. The stiffness of the slideways/stages system is often dependent on and limited by the ball screw-lead mechanical structure, the advantage of using cross-coupling-control for machining high precision complex surfaces would not be well demonstrated. In late 1990s, however, multi-axis slideways/stages using linear motor direct drive were started as almost the 'standard' design configuration for ultraprecision machines and other precision engineering applications [4]. Typically, the aerostatic bearing direct drive stages/slideways on these machines have become more technically complex because of the high precision mechanical components, electrical direct drives, encoders as positioning feedback and advanced control algorithms involved and consequently the dynamics of the system highly dependent on the mechatronic system control, which further challenge the design and development of such mechatronics dominated products. In this study, the simulation result proved that biaxial cross-coupling controller with contour error compensation algorithm have great potential and positive influence on the design and development of aerostatic bearing stages and may contribute to integrated adjustment, error optimization, increased stability and continuous improvement for the whole motion system.

2. Multi-axis aerostatic bearing stage system working for high precision

The motion system of aerostatic bearing stage can be roughly divided into three parts: the mechanical actuation system, the motion control system, and the related algorithms, as shown in Figure 1.

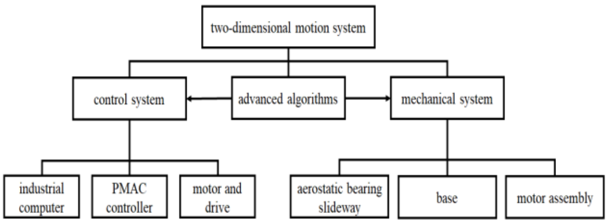


Figure 1. Composition of biaxial stage motion system

2.1 Single-axis motion/positioning system

As the basic unit of ultraprecision motion system, aerostatic bearing slideway relies on an external source of high-pressure air to generate appropriate load-carrying capacity. The principle of aerostatic bearing slideway is to generate an air film between the moving part, which is driven by a linear motor and the stationary part; this air film acts as the lubricant during the relative motion. The mechanical structure and the control system block diagram for a single aerostatic bearing slideway is shown in Figure 2. Although the stiffness of air film is normally lower compared with other lubrication material like oil, but it generates lower heat and surface adhesions at the same time, which give the slideway an extremely long service life and low ratio damping [5].

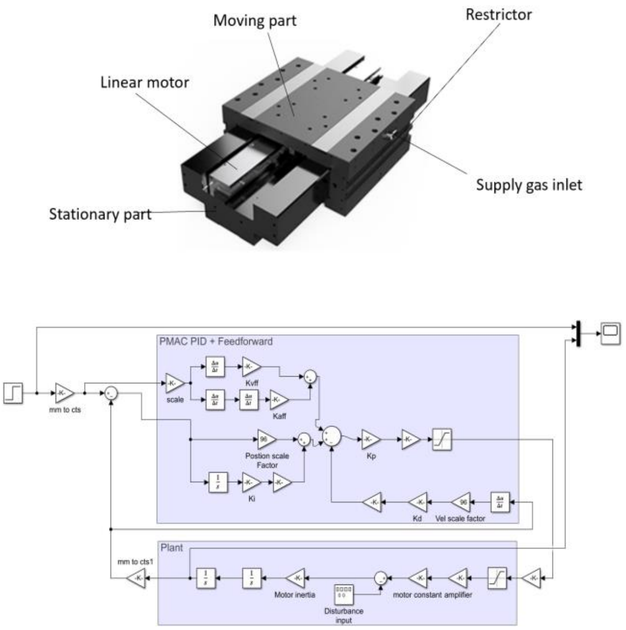


Figure 2. The aerostatic bearing slideway with linear drive and its control system block diagram (in MATLAB programming)

2.2. Biaxial coupled control system

Depending on the control method, biaxial control systems can be classified as uncoupled or coupled. Uncoupled control focus on the corresponding motor for each single axis, through the improvement of single-axis performance, for example, the design and development of large gain controllers, feed-forward controllers, etc., in order to reduce the tracking error of whole system. However, when another motion axis is involved, the synchronization or coordination problem cannot be effectively solved if another axis is not able to receive the real-time dynamic information (e.g., the change of load, speed, etc.) about the changing axes and adjusts accordingly. In addition, the dynamic performance of each axis is usually affected by factors such as load or noise disturbances, so uncoupled control has certain limitations in the complex coordination system which requires high speed and high motion accuracy.

Coupled control is an overall control strategy for multi-axis motion systems. The cross-coupled controller (CCC) is based on the tracking error of each axis and able to directly reflect the contour error, then the position compensation value of each axis is obtained by computing through the cross-coupled controller and finally added to each axis as a gain, thus ensuring that one axis can adjust to the dynamic characteristic changes of another, and ultimately eliminating dynamic effects between axes so that to improving coordinated control performance. The block diagram of CCC based control system is shown in Figure 3:

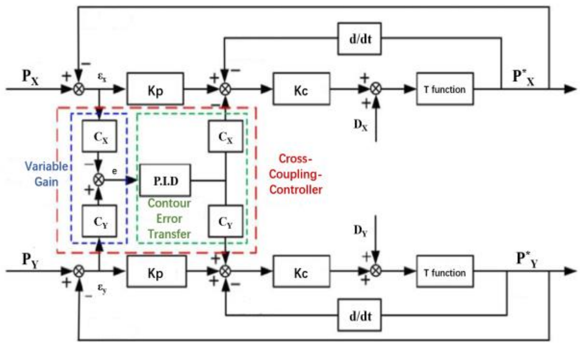
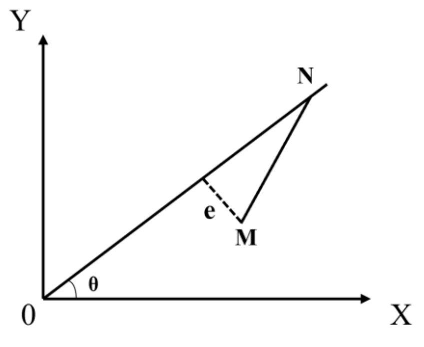
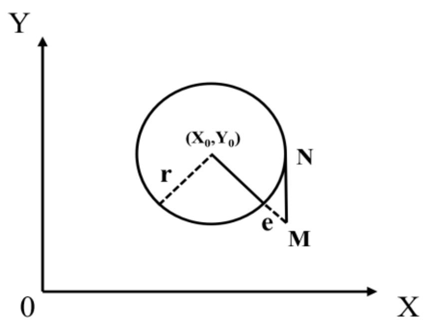


Figure 3. Block diagram of CCC based control system

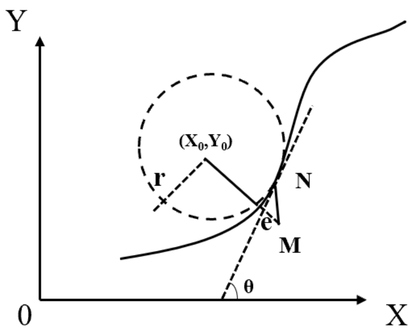
As illustrated by figure 3, control systems of each axis are coupled through CCC. The value difference between input signal and feedback signal from one axis is calculated as tracking error, which is converted into the contour error through the algorithm before input to the CCC (which is internally controlled by a PID) and then returned to each axis though the variable gain C_X and C_Y. The principle of contour error is shown in Figure 4.



(a)



(b)



(c)

Figure 4. Principle of the contour error

Figures 4(a), 4(b), 4(c) are three types of contour errors, i.e. 4(a): linear; 4(b): circular (radius *r*, center coordinate X_0, Y_0); and 4 (c): generic (dashed circle is the inscribed circle of the corresponding curve at the point N). Where: The curve in the diagram is ideal trajectory, at a given moment the desired position of stage is N while the actual position is M, so line MN is the tracking error ε of stage, divided by each axis into ε_x and ε_y. According to the definition, contour error is the shortest distance from point M to the trajectory and is represented by the dash line, with e as its length.
According to the control theory and analysis [2], the contour error is calculated as follows:

Type (a): $\mathrm{e} = \mathrm{MN} = \varepsilon_y \cos\,\theta - \varepsilon_x \sin\,\theta$

Type (b): $\mathrm{e} = \sqrt{(X_0 - x)^2 + (Y_0 - y)^2} - r$

Type (c): $\mathrm{e} \approx \left(\sin\,\theta + \frac{\varepsilon_x}{2r}\right)\varepsilon_x - \left(\cos\,\theta - \frac{\varepsilon_y}{2r}\right)\varepsilon_y$

When the value of is relatively big, type (c) can be simplified as:
Type (c)*: $\mathrm{e} \approx e_x \sin\,\theta - e_y \cos\,\theta$

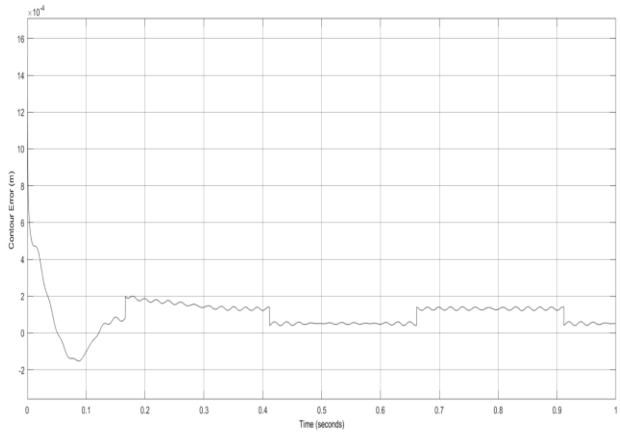
Where:
θ is the angle between the tangent line through the point and the x-axis, with:

$$\theta = \tan^{-1}\frac{dy}{dx}$$

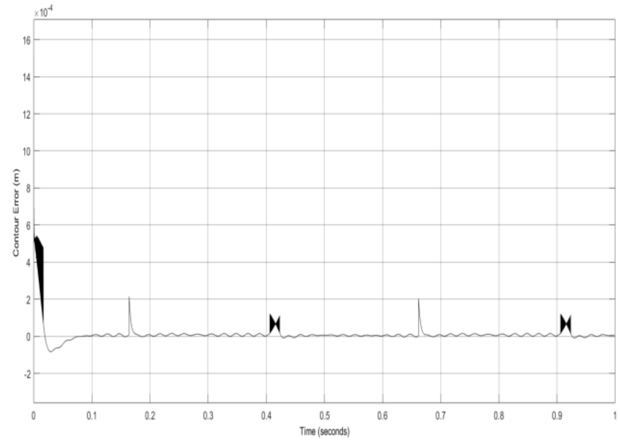
The contour error is normally caused by the uncoordinated movement of displacement velocity of single axis motion and is an important component in assessing the accuracy of motion control. The aim of CCC is to establish a real-time contour error model and making the corresponding compensation for each coordinate axis, thus to reduce or ideally eliminate it. The following simulation will use circular trajectory as an example.

3. Simulation results

Based on the theoretical principles of the previous chapters, the model was created in the MATLAB Simulink environment. The trajectory is set as a circle with radius 1mm, input signal frequency 2*PI*2 for each axis. After initial tuning of the single axis control system, CCC is implemented for coupling the whole system, in order to simulate the actual working environment, the disturbance of 2N/50Hz for X axis and 1N/44Hz for Z axis are added. The results are shown in Figure 5:



(a) Contour error without applying CCC



(b) Contour error with applying CCC

Figure 5. Simulation results of the system contour error.

As illustrated, the average contour error after 0.2 sec is reduced from 0.107 mm to 1.816 μm.

4. Conclusions and discussion

The simulation from the programming environment of MATALB Simulink shows that for biaxial motion control system, the applying of variable gain cross-coupling controller can reduce the contour error to a certain extent, and thus achieve a better accuracy. This further reveal the possibility of cross-coupling-control method for being used as an enabling methodology for development the control system of high precision aerostatic bearing stage products. Through this approach, it is also likely to reveal the collective effects of contour error compensation on the system dynamic performance, and to develop a forward-looking design method for future aerostatic bearing stage control systems.
Explorations on implementation perspectives of this approach are worth further discussed. For a future-oriented precision machine platform, the reconfigurability and the ability to be combined with digital twin system is necessary. According to the above discussed CCC technology, this kind of integrated tuning and compensation method can assistance single slideway product directly integrated as a multi-axis stage, it is more in line with the future trend of manufacturing smarter and more flexible ultra-precision machine platform products and realize the function of “plug and produce” function for digital twin system.

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