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A prediction and evaluation system of the impact factors on the performance of the aerostatic slider

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ABSTRACT

In order to evaluate the effect of the diameter of the restrict orifice and the gas film gap on the performance of the aerostatic slider, cross-correlation analysis method and neural networks should be used to predicate and evaluate the influence degree and the impact factors. The load capacity and stiffness of the airflow film with different diameters and gas gaps are calculated with the modified Reynolds equation, and the prediction and approximation value are showed by the BP neural network.

The correlation degree between the stiffness, which predicated by the neural network and the experimental results of the stiffness is obtained with the cross-correlation analysis method. The correlation coefficient of the stiffness of the gas film thickness and measured result is close to 1, which indicates that the gas film thickness of the slider is the main errors in test results. It provides the evaluation method to identify the effect of the influence factors on the performance of the aerostatic slider.

1. Introduction

Aerostatic guideways have been employed in several state-of-the-art applications in science and technology, and have been considered as important machine elements for ultraprecision machine tools and measuring equipment. Aerostatic bearings support the sliding components with externally pressurized very thin air films with very low frictional characteristics, which have been proven by Shinno et al. [1]. However, those advantages of aerostatic sliders cannot always be fully utilized within some limitations. In particular, the low specific stiffness and liability of developing negative damping may lead to pneumatic hammering in certain working conditions. Aerostatic sliders are prone to a type of self-excited vibration known as "pneumatic hammer" by Farid [2]. In other words, dynamic stability represents an additional limit-line for guideway design optimization. However, in consideration of dynamic stability, we are expected to predict its results and eliminate the negative factors by modifying either guideway or supporting structure or both. A novel flexure-based kinematically decoupled XY positioning stage directly driven by two linear motors was presented by Wang et al. [3]. It can provide larger motion stroke in the developed stage, and it is easy to increase the motion stroke through increasing the guide length.

The instabilities caused by internal mechanisms are rarely considered. Currently, the investigation of the aerostatic sliders focuses on the relationship between the motion errors of the axis' carriage and the slider's geometric errors (Ekinci et al. [4]). In ultra-precision machining, conventional linear aerostatic slider appears large deviation in straightness and parallelism tolerance between the granite sliders, though the aerostatic slider is stable at equilibrium point, a sudden small displacement will cause air vortices and instable motion. The thickness of the air film will be varied with the oscillation and the instability of the aerostatic slider will influence the positioning accuracy of the aerostatic guideway. However, the relation between the air vortices and the instabilities of aerostatic sliders caused by the sudden small displacement has not been analyzed. Previous research focused on static and dynamic performance of aerostatic bearings (Nakamura and Yoshioka [5]; Nakamura and Yoshioka [6]; Yoshimoto et al. [7]). In the proposed research, there is high capacity and stiffness in the aerostatic thrust bearings.

But it is prone to produce pneumatic hammer instability (Bassani et al. [8]). The aerostatic slide system driven by a DC motor with brushes that introduce friction to the system is studied by Mao et al. [9]. The variation of the parameters of the gas film in the working process of the aerostatic guideway is very complex. The signal features of the aerostatic guideway vibration caused by the gas film fluctuation were analyzed and evaluated by Chen et al. [10]. However, the reason of the gas fluctuations is unclear. A rotating cylinder workpiece was used to measure the horizontal motion error of the Z-slide of an ultra-precision diamond turning machine, but the effect of the internal gas film on the slider error was not analyzed (Gao et al. [11]).

A type of aerostatic thrust bearings with small feedholes, which achieves higher performance parameters, was proposed and verified by Nishio et al. [12]. A high-performance aerostatic XY table was presented

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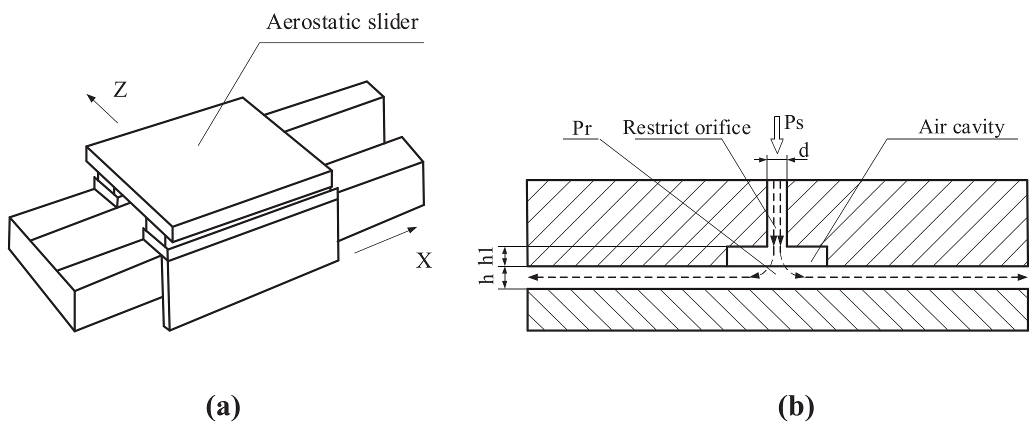

Fig. 1. (a) Configuration of the guideway; (b) air cavity of the aerostatic slider.

by Liang et al. [13], which was directly driven by two LVCAs and supported by aerostatic bearings to realize high-precision positioning motion. The static and dynamic performance characteristics of the journal bearing were analyzed by Kalakada et al. [14]. The behavior of the air flow in the bearing clearance of the aerostatic sliders was analyzed with the "Star-CD" software by Aoyama et al. [15], and the mechanism of the small vibration of aerostatic sliders was suggested and experimented. Dynamic performance of an eccentric squeeze film with nonlinear characteristics was analyzed by Zhao et al. [16]. Moon et al. [17] researched the effects of the key influencing factors including air-oil lubrication, the oil discharge quantity, oil discharge interval, oil viscosity, compressed air flow rate, tube length, and so on. A new method with laser beam to control the permeability of porous bushings for aerostatic bearings was proposed by Yamada et al. [18]. The Characteristics and performance of the aerostatic bearing can be obtained from the above references, however the impact factors on the performance of the aerostatic slider bearings cannot be confirmed. In this paper, a model of the impact factors is established, where the load capacity and stiffness under the Rarefied Effect is established with the modified Reynolds equation. Meanwhile, the neural network and correlation analysis methods are used to predict and evaluate the reason and influence of the behavior of aerostatic sliders. In the paper, the specific degree of the impact factors is proposed both numerically and experimentally.

2. Numerical analysis the behavior of the slider

2.1. Aerostatic slider

In the paper, an aerostatic guideway experiment platform is researched, the frame as shown in Fig. 1(a). The motion of the aerostatic slider is supported with the air film between the slider and guideway, which includes four air cavity, and the restriction type of the air cavity is orifice. The concrete structure inside the slider is shown in Fig. 1(b). The high capacity and stiffness of aerostatic slider is realized by some kind type of parameters, such as the clearance h (in Fig. 1(b)) between the slider and guideway, the diameter d (in Fig. 1(b)) of the restrict orifice, and the supply pressure Ps (Fig. 1(b)). In order to study the effect of the above parameters on the performance of the slider, the gas film pressure in the air cavity is calculated.

2.2. Pressure of the gas film in the cavity

The flow state of the air film in the clearance of the air cavity is one of the key impact factors to the performance of the aerostatic slider. The value of the gap between the slider and guideway is 10 μm. In the paper, the fluid continuous flow equation is used to calculate the flow state in the air cavity, and the gas film pressure distribution is given by Cozzolino et al. [19].

$$\frac{\partial}{\partial x}\left(ph^3\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(ph^3\frac{\partial p}{\partial y}\right)=12\eta\frac{\partial(ph)}{\partial t}+6\eta u\frac{\partial(ph)}{\partial x}+6\eta v\frac{\partial(ph)}{\partial y} \tag{1}$$

In which, h is the film thickness in y direction, and x-z plane is solid surface contacted with the gas film. p is the air pressure, and η is the dynamic viscosity of the air. u, v and w express the gas flow velocity in x, y and z direction respectively, where v is approximately equal to zero since it is much smaller than u and w. t is the time parameter.

The gas film velocity equations in X and Y directions are $\frac{\partial p}{\partial x}=\eta\frac{\partial^2 u}{\partial y^2}$, $\frac{\partial p}{\partial z}=\eta\frac{\partial^2 w}{\partial y^2}$, $\frac{\partial p}{\partial y}=0$, the state equation of the air is $P=\rho\cdot R\cdot T$, and the continuity equation is $\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}+\frac{\partial\rho}{\partial t}=0$.

The value of the gas film gap of the aerostatic slider belongs to micro scales. The microscopic level of the gas flow is typically classified into four flow regimes according to their Knudsen number, which is defined as the ratio of the molecular mean free path (λ) to the characteristic length (L) and is written as: $Kn=\lambda/L$. The four areas are continuum region ($Kn<0.01$), slip slow region ($0.01<Kn<0.1$), transition region ($0.01<Kn<10$) and free-molecule region ($Kn>10$) respectively. In this model, the characteristic length L is 10 μm, and λ is the gas molecular mean free path. With the parameters λ and L, the value of the Knudsen number $0.01<Kn<0.1$ is obtained. In this case, the continuous hypotheses of the medium flow are no longer valid. Therefore, the velocity slip effect of the gas film needs to be considered. The boundary condition of the velocity slip is important for the performance of the guideway. As shown in Fig. 1(a), the movement direction of the aerostatic slider is X direction. The movement of gas film is mainly along the X direction and leads to velocity slip, so the velocity slip factor is introduced to the traditional Reynolds equation. The boundary condition of the first order velocities slip is expressed as follows (Kuo and Chen [20]):

$$y=0,\quad u=\mathrm{U}+l'\frac{\partial u}{\partial y},\quad v=l'\frac{\partial w}{\partial y},\quad w=0 \tag{2}$$

$$y=h,\quad u=\mathrm{U}-l'\frac{\partial u}{\partial y},\quad v=-l'\frac{\partial w}{\partial y},\quad w=0 \tag{3}$$

where, λ is the average free path of gas molecules, $l'=\frac{2-\sigma_v}{\sigma_v}\cdot\lambda$ is the slip length of the gas, and σ_v is the tangential momentum adjustment coefficient of the molecule. The modified Reynolds is deduced from above equations:

$$\frac{\partial}{\partial x}\left(ph^3\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(ph^3\frac{\partial p}{\partial z}\right)=\frac{12\mu lU}{{h_m}^2p_0\left(1+6k'_n\right)}\cdot\frac{\partial(ph)}{\partial x}+\frac{24\mu lU}{{h_m}^2p_0\left(1+6k'_n\right)}\cdot\frac{\partial(ph)}{\partial t} \tag{4}$$

where $k'_n=\frac{2-\sigma_v}{\sigma_v}\cdot k_n$.