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Technical note

Non-contact position control via fluid shear force

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ABSTRACT

Non-contact position control of components is beneficial to avoid wear, damage, and nonlinearities associated with friction. Air bearings, in particular, offer non-contact, high stiffness guidance, but no means of controlling the position of the supported component. In this work, we investigate the use of shear force resulting from the air bearing fluid flow as a means of actuation. Shear force actuation is tested in an air bearing slumping system, where a flat, horizontally placed glass substrate is supported on both sides by top and bottom air bearings. We investigate the use of two methods of substrate position sensing: a fiber-optic sensor and a machine vision sensor. We show that the glass substrate position can be successfully controlled by using fluid shear force. The magnitude of the fluid shear force is measured. System identification is performed, and the results are shown to agree with a second-order model.

1. Introduction

Frictionless mechanical elements and actuators are highly desirable in precision machines, where nonlinearity and hysteresis arising from friction can have a significant impact on positioning repeatability and accuracy. While frictionless guidance elements, such as flexures, magnetic bearings, and air bearings, can guide structures with excellent repeatability, the actuators themselves typically introduce friction and stress concentrations.

Air bearings are generally used with gaps smaller than 10 μm and provide nearly frictionless bearings [1]. Viscous forces are dominant over inertial forces in thin, long gaps in which the lubrication approximation is valid [2]. In lubrication flows, the fluid can support large loads and impart significant shear force on the object surface. When a planar air bearing is perfectly parallel to an object surface, the pressure distribution, and therefore the flow, of the fluid film is radially symmetric, so there is no net shear force on the surface. If a wedge angle is imparted, the shear forces become asymmetric due to a shifting pressure distribution [3], and a net shear force arises. This concept is shown in Fig. 1, and has been modeled in Ref. [4]. Since this shear force is applied over the entire surface, stress concentrations are avoided. Devitt et al. [5] have reported using shear force as an actuation method for flexible films moving over cylindrical air bearings, to control tension of the film and to provide increased cooling, cleaning and drying of the film. van Rij et al. [6] and van Ostayen et al. [7] have used shear stress to control wafer position, by implanting an air bearing with many cells whose pressures may be independently controlled. This allows control of the direction of flow. The same effect may be achieved more simply, for our purposes, by wedging a top and bottom air bearing with the wafer in between, which is the method investigated in this work.

The motivation for the present work is to investigate the use of fluid shear force for actuation in a non-contact glass slumping device using air bearings, which is to be used in the fabrication of high-precision thin optics for X-ray telescopes. In this application, a flat, round glass substrate floats between two porous air bearings, and, as the device and glass are heated, the glass softens and conforms to the figure of the air bearings. The method of actuation researched by van Rij et al. [6] and van Ostayen et al. [7] cannot be used for slumping, because the softened glass at high temperatures will droop and touch the bearing, if it is not supported on both sides symmetrically.

Position control is required because the glass is in an unstable equilibrium. It is critical to have non-contact position actuation and sensing, which does not induce stress concentrations, in order to

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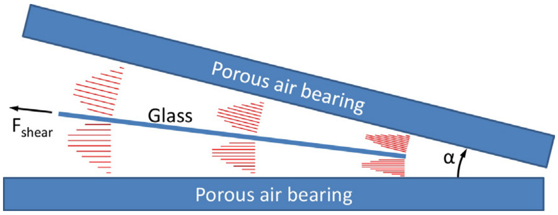

Fig. 1. Illustration of net shear force arising from wedge angle, α.

avoid introducing deformations in the glass, which can arise from even small concentrated forces while the glass is soft. For example, the simplest method to keep the glass centered in between the two bearings would be to add a physical stop around the circumference. However, it was discovered that any such physical stop, which is a small concentrated force, induces ripples in the glass geometry.

Non-contact slumping offers a distinct advantage over traditional contact slumping: mid-spatial frequency errors are not introduced. In contact slumping, glass is placed on a mandrel, with a release layer between the two (to prevent the glass from fusing to the mandrel), and heated to the softening point of the glass. Gravity forces the glass to conform to the figure of the mandrel, but any non-uniformity of the release layer, due to either clumping or dust particles, introduces mid-spatial frequency errors in the slumped glass. These errors adversely affect the angular resolution of X-ray telescopes, and are difficult or impossible to remove using figure correction techniques [8]. Non-contact slumping on air bearings avoids this issue by replacing the solid or powder release layer with an air film. In addition to not introducing ripples, this air film allows significantly faster slumping cycles since the glass is not in contact with a mandrel, which is a large mass with a significantly different coefficient of thermal expansion than that of glass. A long cool-down time, on the order of days, is required to minimize figure errors due to this mismatch in the coefficients of thermal expansion.

2. Slumping device prototype design

Investigating the use of shear force as a means of position control requires a device with air bearings capable of supporting a glass substrate and imparting a controllable wedge angle to generate shear forces. The device shown in Figs. 2–4 is a non-slumping (room temperature) prototype that is meant to only validate the usage of fluid shear force as an actuator. This initial device does not need to actually slump glass, so it does not need to withstand high temperatures. Although the method of position sensing used in the 600 °C application is presented in Section 2.2, the complete design of the final slumping (high temperature) device is not presented in this paper.

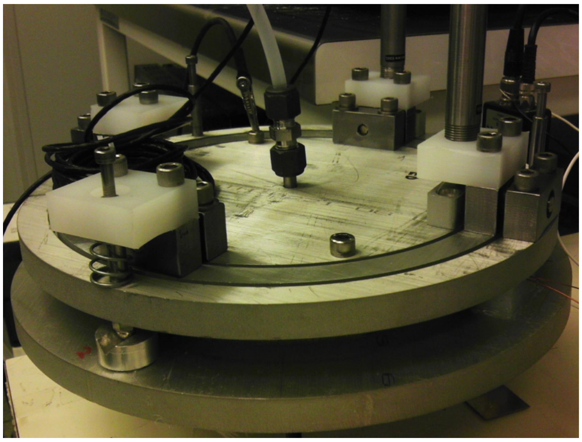

Fig. 2. Photo of device used to control glass position between two air bearings.

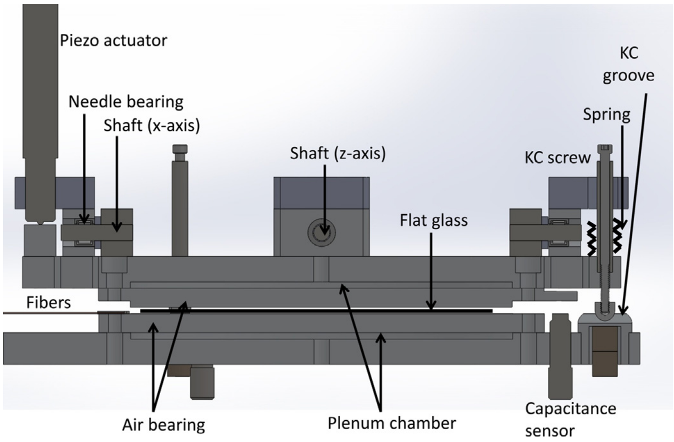

Fig. 3. Cross-sectional view of the device in a perfectly stable position.

2.1. Mechanical design

The slumping device, described in detail by [9], can be divided into two subassemblies, top and bottom, which are mated together through an adjustable kinematic coupling (KC). The purpose of the kinematic coupling is to enable repeatable positioning of the subassemblies with respect to each other after removal of the top assembly for maintenance. Each subassembly holds a porous air bearing and a plenum chamber. The two air bearings face each other with a tightly controlled gap, in which a substrate is placed. The bottom subassembly stays stationary and provides the bottom support for the substrate. The top subassembly works as a 2-axis gimbal to angle the top air bearing in relation to the bottom bearing to provide a directed shear force.

Fig. 5 illustrates the exaggerated kinematics of the top subassembly. The outer ring mates to the bottom subassembly using the KC adjuster screws, which rest in the KC grooves on the bottom subassembly. The outer ring remains stationary, while the inner ring and bearing/plenum combination each provides rotation about a quasi-horizontal axis (x and z axes). Three capacitance sensors (HPT-150F-V-N2-3-B "V" series probes from Capacitec) are mounted to the bottom subassembly, and provide

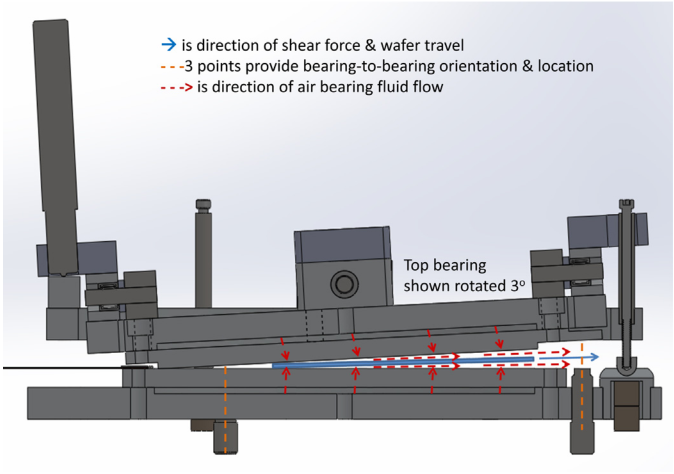

Fig. 4. Cross-sectional view of the device illustrating rotation of the top bearing to impart a shear force.