Centrally fed orifice based active aerostatic bearing with quasi-infinite static stiffness and high servo compliance

N. Maamari[a],[*], A. Krebs[a], S. Weikert[b], K. Wegener[b]

[a] *ETEL S.A, Môtiers, Switzerland*
[b] *ETH Zurich, Institute of Machine Tools and Manufacturing (IWF), Zurich, Switzerland*

ABSTRACT

Active compensation of aerostatic bearing enhances their inherent limited stiffness and adds macro positioning capabilities. Current active solution relies on a position feedback to reach high stiffness. In this study, a novel concept that replaces costly position feedback by a self-regulating stiffening mechanism is investigated. This concept features a guided conical deformation based on integrated leaf springs. This balances the pressure and servo induced deformation, leading to quasi-infinite stiffness and high servo compliance. A lumped and a finite element models governing the static behavior are presented and benchmarked. Open loop stability is assessed using a linearized lumped dynamic analysis, and solutions based on a mechanical and a mechatronic approach are proposed. Finally, the prototype is tested in open loop, proving a quasi-infinite stiffness and a servo compliance of 3.4 $\mu m/A$.

1. Introduction

Aerostatic bearings have been extensively used in precision motion systems, specifically in semi-conductor manufacturing and inspection. The absence of stick-slip in aerostatic bearings results in a precise and repeatable motion. Air pads are generally classified based on the type of inlet restrictor [1]. Centrally fed orifices-based compensation sketched in Fig. 1 are commonly employed due to their ease of manufacturing. Pressurized air is forced into the pad with a supply pressure p_s. The orifice acts as an inlet restrictor, and the exhaust restrictor is composed by the thin gap between the guideway surface and the pad's lower surface. Loading/unloading the pad changes the pressure distribution $p(r)$ resulting from the alteration of the gap height h and the recess pressure p_{rec}.

One of the disadvantages of air bearings is their limited specific stiffness, consequently multiple configurations have been attempted to enhance the stiffness. Fourka et al. [2] benchmarked the impact of different types of inlet restrictors and demonstrated that pads with porous restrictor and low permeability achieved the highest static stiffness mainly due to a uniform pressure distribution.

Alternatively, static stiffness can be increased by changing the exhaust restrictor. Rowe and Kilmister [3] presented the first type of passive load compensation. A deformable membrane replaced the pad's lower surface. In this case, the response of the pad involves both rigid body motion and the deformation of the membrane. Franken and Hagen [4] added a pivoting membrane which allowed an infinite static stiffness. Enderle and Kaufmann [5] extended the range of infinite stiffness by using inner and outer gas chambers. Snoeys et al. [6] also achieved infinite stiffness with a simpler design using a single chamber, where the pressure is equal to the gap inlet pressure p_{rec}. Bryant et al. [7] established a design chart based on optimization methods to obtain infinite static stiffness. The main disadvantage of these passive load compensation methods is the requirement of a pressurized chambers increasing the manufacturing complexity. Additionally, the geometric inaccuracies of the guiding surfaces remain uncompensated leading to tool point errors Jaumann et al. [8]. Actively controlled air bearings offer a way to overcome these limitations and add a macro-positioning capability to compensate for the geometrical inaccuracies of the guiding surface.

Active compensation strategies can be grouped into two categories: flow restriction control and gap geometry control. Morosi et al. [9] and Pierart et al. [10] achieved upstream pressure control using a piezo actuator on a journal bearing. The piezo regulated the supply pressure p_s resulting in a controlled radial injection of fluid into the bearing. Huang et al. [11] described alternative means of actuation based on magnetostrictive material. Similarly up stream control was implemented by Ghodsiyeh et al. [12] using a diaphragm valve to pneumatically control the feed pressure. Their results showed 40% increase

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Nomenclature

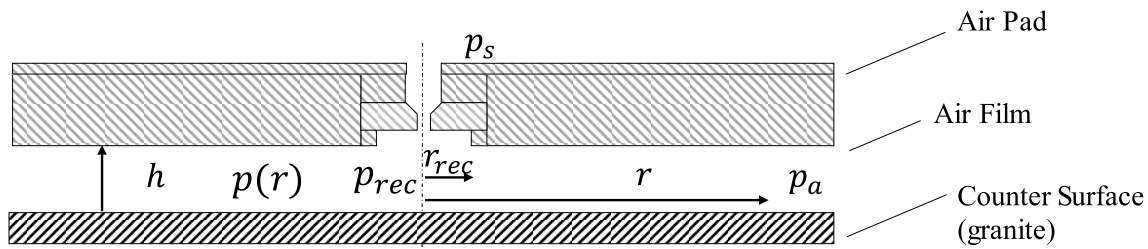|			
A_{inh}	area of the annular inlet region	$J_{\varepsilon_x}(x)$	Jacobi operator: $\partial\varepsilon_x(x)/\partial x$
A_{ori}	area of the nozzle cross section	k_m	conicity stiffness
B_g	magnetic flux in the air gap	k_p	pad stiffness
B_r	remnant magnetic flux	k_t	motor constant
B_v	exhaust restrictor	L	distance between low/up plates
B_{vD}	exhaust restrictor distributed model	$\dot{m}_i$	mass flow rate
B_{vL}	exhaust restrictor lumped model	N	number of turns of copper coil
C_h	gap compliance	η	dynamic viscosity
C_s	pad servo compliance	p_a	ambient pressure
F_L	load capacity	p_{rec}	recess pressure
F_{Max}	maximum load capacity	p_s	supply pressure
F_N	Normalized load capacity	$p(r)$	pressure distribution
F_s	servo force	r	radial distance
ε_{Bv}	Error of the exhaust restrictor between distributed and lumped model	r_a	pad radius
		R_{air}	specific gas constant
h_I	gap height at the interface	R_i	magnetic reluctance
h_p	gap height at the pivot radius	r_{ori}	orifice radius
h_{pa}	gap height difference	r_p	pivot radius
h_{rec}	gap height at the gap entrance	r_{rec}	recess radius
$h(r)$	gap geometry	r_s	voice coil moment arm
I_s	servo current	v	conicity angle
		μ_r	vacuum magnetic permeability
		μ_0	relative magnetic permeability

Fig. 1. Representation of centrally fed orifice-based air pad.

is static stiffness. Further down-stream control involves regulating the recess pressure by controlling the opening of the inlet restrictor. Mizumoto et al. [13] developed an Active Inlet Resistance (AIR) for a journal and axial thrust bearing using a piezo-actuator. This allowed a change in the pressure distribution without a disturbing the film geometry. The main limitation of flow restriction control is in its limited bandwidth caused by the latency in the response [14].

Gap geometry control offers a collocated actuation. In this approach, the force is directly injected into the gap and instantly changes the pressure distribution. Ro et al. [15] described a simple method of gap actuation. The linear axes used four iron core motors with permanent magnets to actively preload a set of eight porous media air bearings. Additionally, feedforward compensation and laser interferometer measurements were implemented to reduce geometrical inaccuracies from ± 1 μm to ± 0.11 μm in the vertical direction. Since the motors are acting against the inherent stiffness of the pad, a low mechanical stiffness is required to ensure optimal servo compliance with acceptable force density.

Al-Bender et al. [14] developed a novel active bearing based on gap deformation control using piezo-actuators. This approach achieves a gap activation without reducing the mechanical stiffness. A high-end capacitive measurement was needed to ensure high stiffness for disturbance rejection. Van Ostayen et al. presented another design by combining the configurations as presented by Al-Bender et al. [14] and Kilmister [3]. The active pad supported in the center, consisted of a flexible plate with intermediated circumferential support, and an electromagnetic actuator mounted on the edge of the pad to deform the plate. This method increases the design complexity because it involves a plate deformation. A membrane like thin plate was required to obtain

high mechanical stiffness comparable to passive load compensation levels. However, membranes like thin plates under point loading (i.e.: servo force) only lead to local deformation. Thus, the servo force will not impact the pressure and gap height across the whole pad, limiting the servo's impact on the load capacity [16].

The main disadvantage of current active methods [11,12] is the need for gap sensing. The stiffness of the active pad is generated from the controller proportional gains. This adds a high requirement on resolution and linearity of the position sensor, which needs to cope with the planar motion of the pad on a non-conducting surface of the granite. The field of positioning systems would benefit from the development of an aerostatic bearing with high passive mechanical stiffness for disturbance rejection without the requirement of gap measurement, while maintaining a high servo compliance to compensate the geometrical inaccuracies of the guideway surface.

This work presents an alternative active aerostatic bearing based on conicity actuation. The current design perfectly balances the pressure and servo induced deformation, thus any load capacity within theoretical limits is attainable with low actuator forces.

The final goal is to control the active pad in closed loop without any gap sensing measurement using either a velocity or conicity feedback. However, a characterization of the static behavior and the open loop stability is essential before the development of a control architecture.

This article presents the mechanical concept and the governing equations based on a static lumped approach. A dynamic lumped model is used to assess the stability of the pad in open loop. Later, the mechanical design is presented and a Finite Element (FE) model encapsulating the solid deformation, thin-film flow and magneto-static actuation is compared to the lumped approach. The results of the