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Numerical and experimental study on the influence of material characteristics on the levitation performance of squeeze-film air bearing

Minghui Shi, Lin An, Kai Feng*, Zhiyang Guo, Wanhui Liu

State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, 410082, China

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ABSTRACT

This research investigated the effects of material characteristics on the load-carrying capacity of squeeze-film air bearings (SFABs). Bearings with the same size and structure but are made of different materials, namely, aluminum (AL 2024), brass (CuSn35), and spring steel (60Si2Mn), were manufactured and tested. A theoretical analysis model was established to investigate the levitation performance of SFABs by coupling the near-field acoustic levitation (NFAL) and flexure pivot-tilting pad models. A test apparatus with the facility of measuring the floating performance of a shaft was designed and fabricated. Studies have shown that material characteristics are extremely important for the levitation performance of SFABs, and aluminium (AL 2024) was identified as the most suitable materials among the three materials.

1. Introduction

Increasing demand for high-speed and high-precision manufacturing equipment has given rise to the development of non-contact bearing [1,2]. Currently available non-contact bearing, such as aerostatic/aerodynamic bearings [3–5] and electromagnetic bearings [6,7], have been applied in many applications. However, these bearings have many drawbacks, such as high friction and wear during the start and stop phases of operation (aerodynamic bearings), need of constant pressurized clear lubricant supply (aerostatic bearings), and strong magnetic flux and complex structure (electromagnetic bearings). Squeeze-film air bearings (SFABs) based on near-field acoustic levitation (NFAL) have drawn much attention for its advantages of not requiring external pressurized air supply, compact structure, and environmental adaptation [8,9].

NFAL is observed when a planar object is placed upon an oscillation sound radiator at a frequency above the audible range. The object can be lifted through direct radiation of the radiator, and the floating height is normally quite small, which is much smaller than the wavelength of the applied sound wave. Researchers [10–12] have derived the formula of acoustic levitation pressure and squeeze levitation force through different methods. The levitation performance of squeeze film is reported to increase with increasing vibration amplitude and excitation frequency [13,14]. According to the working principle of NFAL, a number of SFABs have been designed over the past few decades. The first SFAB based on NFAL, which was excited by magnetic actuators in an audible frequency range, was introduced by Salbu [15]. Yoshimoto et al. [16] presented a linear SFAB with elastic hinges to increase flexibility of the structure. Following Yoshimoto's research about SFAB, Ha et al. [17] designed a novel squeeze-film journal bearing and investigated the relationship between excitation frequency and floating characteristic. Subsequent studies were carried out by Stolarski [18] and Feng et al. [19]. Later, a new design of non-contact spherical bearing based on NFAL was introduced by Chen et al. [20]. The design can be used for novel supporting bearing of suspended gyro. Stolarski et al. [21] found that the appropriate bearing configuration is critical to the levitation performance of SFAB. To improve the load-carrying capacity of SFAB, Zhao and Wallaschek [22] designed a novel squeeze-film journal bearing, which is formed by multiple independently vibrating surfaces. They pointed out that the load capacity of the proposed bearing can reach 50 N.

Recently, Feng et al. [23] designed a novel SFAB based on NFAL, which is composed of three pads connected to the bearing housing through a straight beam and uniformly distributed along the circumference. In this structure, the straight beam is directly excited by piezoelectric actuators (PZTs), which is beneficial for enhancing the radial vibration amplitude of the pads. The most significant advantage of this structure is that the radiators (flexure pivot-tilting pads) always adapt well to squeeze actions. Importantly, the bearing structure offers the possibility to be operated as an aerodynamic bearing at high rotational speeds and obtain a considerably high load capacity [24]. The bearing structure with pivot-tilting pads can also enhance the stability of rotor systems when the bearing works as an aerodynamic bearing due to low cross-coupled stiffness [25].

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* Corresponding author.
E-mail address: jkai.feng@gmail.com (K. Feng).

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Nomenclature

A	Vibration amplitude of the pad (m)
C	Radial bearing clearance (m)
e	Shaft eccentricity (m)
e_x, e_y	Components of shaft eccentricity displacements (m)
e_w	Amplitude of dynamic deformation (m)
f	Excitation frequency (Hz)
g	Gravitational acceleration (m/s^2)
$F_{P\delta}$, $M_{P\delta}$	Radial force (N), tilting moment (N m) acting on pad caused by air pressure
$F_{mP\delta}$, $M_{mP\delta}$	Time-averaged radial force (N) and tilting moment (N m)
F_{Rx}, F_{Ry}	Loads acting on pad (N)
F_{mPx}, F_{mPy}	Time-averaged force along $x-$ and $y-$ axes caused by air pressure (N)
h, H	Film thickness (m), dimensionless film thickness
$h_{\min}$	Minimum film thickness
h_s, h_d	Static film thickness and dynamic film thickness (m)
K_δ, K_ϕ	Radial stiffness of straight beam (N/m), tilting stiffness of flexure web (N m/rad)
L	Length of bearing
P, p, p_a	Dimensionless gas film pressure, gas film pressure (Pa), ambient pressure (Pa)
O_b, O_s	Bearing center, shaft center
r, R	Outer radius of shaft, bearing radius
r_g	Shaft radial growth (m)
r_p	Pad preload
τ, T	Time (s), dimensionless time
ω	Vibration frequency (rad/s)
Z	Dimensionless axial coordinate
m	Mass of the shaft (kg)
W	Load acting on bearing (N)
ε	Dimensionless eccentricity ratio (e/C)
η	Pad transverse motion (m)
ϕ, δ	Pad tilting angle (rad) and pad radial displacement (m)
α	Tilting angle of the shaft (rad)
β	Attitude angle
θ_p, θ_s, θ_e	Angular position of pivot, pad leading edge, pad trailing edge (rad)
θ, z	Circumferential and axial coordinates
ϑ	Angle of one pad
σ	Squeeze number
μ	Air viscosity (Pa s)

Subscripts

p	Pad
x, y	$x-$,$y-$*axes*
δ, ϕ	Radial, tilting directions

Superscript

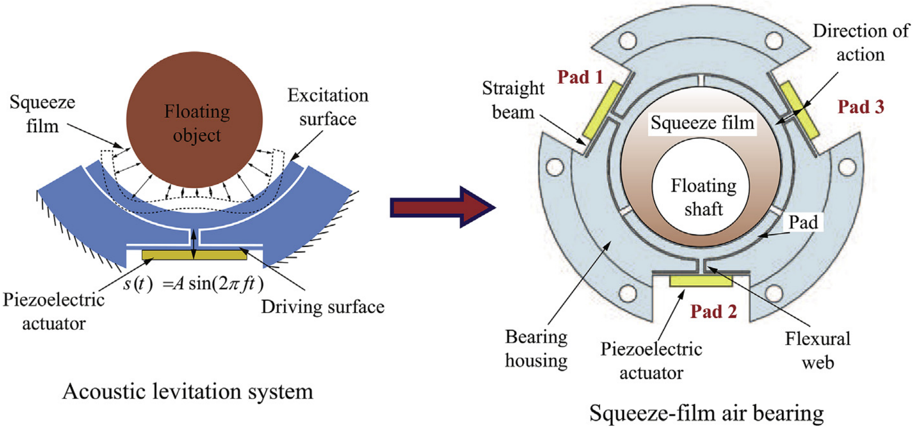
i	Pad squeeze number

In real industrial applications, obtaining a large-enough load-carrying capacity with a compact structure is one of the major issues in the investigations of SFABs. In the NFAL system, high frequency and large vibration amplitude could lead to high air pressure and large load-carrying capacity. SFAB is normally designed to have appropriate stiffness and work at resonant model for large levitation force. For this purpose, rational design of bearing structure, size, and material, which is related to the bearing vibration, plays an important role in the levitation performance of SFABs. Appropriate selection of bearing material may become the only method to improve the levitation performance due to the space and structure limitation in many applications. Thus, the effect of material characteristics on the performance of SFABs should be investigated. Accordingly, in the present work, a comparative study on the floating performance for three test SFABs made of different materials, namely, aluminum (AL 2024), commercial brass (CuSn35), and spring steel (60Si2Mn), was presented. An experimental test rig and measurement system was developed to measure the floating performance of a shaft supported by the three test bearings. Parametric analyses on the effects of input voltage, eccentricity ratio, frequency, and radial clearance on the squeeze effect were also discussed. This work can serve as a reference for a better understanding on the levitation mechanism and further design and application of SFABs.

2. Description of SFAB and its mode shape

2.1. Bearing configuration and working principle

The configuration of the novel SFAB is shown in Fig. 1. PZTs were attached to the slot surfaces in the circumferential direction of the bearing with the help of an epoxy resin. When the PZTs were excited by an AC sinusoidal voltage, the excitation surface produced periodic motion along the radial direction, which led to the continuous expansion and compression of the air gap between the floating object and excitation surface. A high air pressure (actually time-averaged pressure) was generated by the periodic vibration, which was the source for the levitation force. Therefore, the floating object can be stably levitated.



Acoustic levitation system

Squeeze-film air bearing

Fig. 1. Schematic of acoustic levitation system and SFAB structure.

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