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A non-contact linear bearing and actuator via ultrasonic levitation

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Abstract

In this study, the design and testing of a linear bearing using near-field acoustic levitation (NFAL) phenomenon was performed. A pair of Langevin transducers placed at either end of a beam with either a right-angle V-shaped or Λ-shaped cross-section was used to excite and absorb ultrasonic flexural vibrations transmitted along the length of the beam from one transducer to the other. The beam was used as a guide rail, supporting a slider formed from a short length of beam with the same cross-section. This arrangement provides a small and inexpensive non-contact bearing with magnetic field immunity and without generating a magnetic field, both useful characteristics for clean room and precision actuators. The slider was levitated by the vibration of the beam up to 100 μm, and was moved successfully in either direction by traveling waves transmitted along the guide rail. In a 300-mm long prototype, objects up to 160 g (60.5 kg/m^2) were levitated and transported. A transportation speed of 138 mm/s was obtained for a slider of 90 g. The stiffness of the levitation was found to be 1.1 N/μm/m^2 for this prototype.

Keywords: Acoustic levitation; Linear actuator; Piezoelectric actuator; Clean room; Non-contact actuator

1. Introduction

Linear stages are commonplace in industrial production and research associated with semiconductor, nano-scale, bioengineering, and other technologies where precise positioning is a necessity. Bearings are a fundamental component of and a limiting factor in the performance of linear stages [1]. Linear bearings using contact, including screw actuators [2] and ultrasonic motors [3] have been thoroughly studied.

The screw actuator converts rotary motion to linear motion, providing an easy way to generate linear motion from the rotary output of electric motors, but with backlash and wear problems. Improvements in the mechanism, by including balls or riding rollers in threaded grooves for linear contact with the shaft – the Saginaw mechanism [2] – have improved their performance; Awaddy et al. developed precision positioning methods for such actuators [4]. Ball-screw actuators are common in production process automation, steering systems, and aircraft flight actuators. Despite these advancements, their precision is insufficient for many applications [1].

Linear ultrasonic motors are driven by forces generated between the rotor and the stator, the latter vibrated by piezoelectric elements, generating high linear forces and speeds, with sub-nanometer-order positioning precision [3,5,6].

Such motors have been investigated for several years and are already being used in several practical applications. There are of variety of types and sizes: multilayer piezoelectric actuators [7–10], motors using radial and non-axisymmetric modes [10], a quasi-traveling wave motor [11], a motor using two sandwich-type vibrators [12], self-locking theory [13], two motional function [14], motors using nonresonant piezoelectric effects [15], and a "shaking beam" motor [16], among many others. Motors using surface acoustic waves are an especially powerful version of piezoelectric motors [17,18], but wear and surface treatment failure are especially serious problems for these motors. Unfortunately, wear is a significant drawback not only with all piezoelectric motors using sliding contact, but indeed with all linear actuators that rely on contacting components.

Because of wear, friction, and stiction associated with all bearing systems that rely on contact, for applications that require them, air cushion and magnetic levitation systems have remained the only choices for "frictionless" bearings. Air hockey [19,20] is a pedestrian application of the former technology, where objects

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are suspended on a cushion of air pumped through small holes in the surface of the underlying table. Such technology has far more sophisticated applications in spacecraft and multibody dynamics [21]; in particular, Mori and his associates at the Akita Research Institute of Advanced Technology developed a sophisticated linear actuator [22] using air cushioning. In magnetic levitation, either repulsion or attraction between paired magnetic fields, generated on the slider and fixed rail of the actuator, is used. Motion can be generated by manipulating the interaction of the fields [23]. Due to the inherent instability in this interaction (Crenshaw's theorem), closed-loop control is necessary (with the specific exception of diamagnetic levitation).

Just as in bearings with contact, however, dust accumulation and low-frequency vibrations are a problem. Both systems generate low-frequency vibrations (especially with regard to motion along the axis of the rail), reducing positioning accuracy. Moreover, air bearings require a tremendous amount of pure, clean air. In magnetic levitation systems, the levitated object must be magnetic, and the generation of powerful magnetic fields may attract dust and affect surrounding equipment.

To address these problems, a non-contact linear bearing based on near-field acoustic levitation (NFAL) is proposed here. NFAL is a phenomenon in which a planar object atop a vibrating surface is levitated in the near-field by the acoustic radiation emanating from the vibrating surface [24–29]. Hashimoto et al. [30] illustrate the phenomenon, using a planar plate levitated about one-tenth of an acoustic wavelength from an ultrasonically vibrating surface. The phenomenon has been studied for non-contact ultrasonic motors and non-contact transportation of ultra-clean glass plates for liquid crystal displays. Yamazaki et al., proposed an ultrasonic motor in which the rotor is levitated and driven to rotate at very high speed by the ultrasonic acoustic field radiated from the stator into the air gap between the rotor and the stator [31–33]. To transport an object, flexural *traveling* waves transmitted along an extremely long and flat vibrating plate was devised by Hashimoto et al. [34,35], and it was confirmed that levitated objects could be transported without contact along the long axis of the plate. Further, it has been shown [36] that a retaining force acts on the levitated object to hold it in place over the center of acoustic radiation. However, the retaining force is very weak, permitting objects to move perpendicularly to the long axis of the plate. In this study, flexural traveling waves are transmitted along a V-shaped beam to levitate a slider with an identical cross-section, eliminating the degree-of-freedom transverse to the axis of sliding that was a problem in earlier studies. In this way, stable, precise, and virtually frictionless support and actuation can be obtained, requiring neither special materials for the slider nor a levitation control system.

In what follows, the bearing actuator's concept and design are given, followed by the characteristics of levitating a slider using standing waves excited along the beam. Finally, the slider's linear motion in both directions due to the excitation of traveling waves by the interaction of two transducers placed at either end of the guide rail beam is provided, with details on the strength and fidelity of acoustic levitation as used in this study.

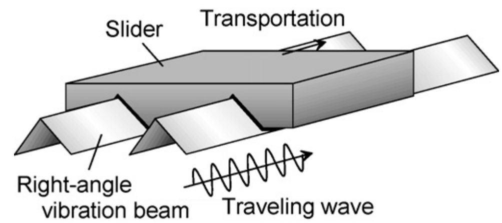

Fig. 1. The basic idea of a non-contact linear bearing using flexural vibration of a pair of right-angle beams (with a "Λ cross-section"). The beam length is considerably longer than shown in this figure. The slider is levitated acoustically above the rails—there is no direct contact.

2. Principle and configuration of the right-angle acoustic levitation bearing

Fig. 1 illustrates the concept of the non-contact linear bearing used in this study. A flexural traveling wave may be excited along the Λ-cross-sectioned beam with the transducer and horn in the shown configuration, permitting the levitation and propulsion of the slider along the guide rail beam. Due to the right-angle cross-section, the lateral position of the slider is tightly controlled.

For this study, two different guide rail configurations were considered for the linear bearing. In both cases, a beam with either a V-shaped or Λ-shaped cross-section was used as both the rail guide and the slider, as shown in the cross-sectional view of the beam and slider for both arrangements in Fig. 2.

The experimental setup used to determine the standing-wave levitation characteristics of the system is shown in Fig. 3. A 2-m long right-angle beam was excited using a Langevin transducer with a stepped horn at 18 kHz. The side length and the wall thickness of the beam were 30 mm and 2 mm, respectively. The transducer is mounted diagonally halfway from the corner of the Λ ($x = 15$ mm), 45 mm from the end of the beam ($z = 0$). Standing waves are excited as the other end of the right-angle beam is free in this configuration.

2.1. Dispersion charctersistics of the right-angle beam analyzed with FEM

Prior to the experiments, the dispersion characteristics of the right-angle beam vibration were analyzed below 30 kHz using the finite element method (FEM). Quadratic quadrilateral shell elements with edge lengths of 7.5 mm were used in the analysis. Matching the experiments, the material was aluminum throughout, with hard PZT complete with anisotropic (∞ mm/6 m) and

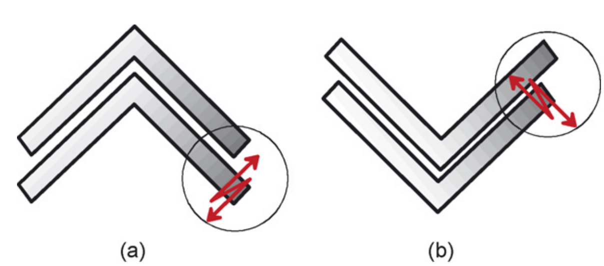

Fig. 2. The difference in the configuration of the beam and slider, shown on-end, for the (a) Λ and (b) V-shaped configurations, indicating the vibration displacement measurement location.