A NON-CONTACT LINEAR BEARING BY ULTRASONIC LEVITATION

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Abstract

In this study, a linear bearing based on Near-Field Acoustic Levitation (NFAL)[1][2] is proposed. A beam with an L-shaped cross-section is used as a guide rail, and a slider of the same cross-section is levitated by ultrasonic bending vibrations excited along the beam. This provides a small and inexpensive non-contact bearing with magnetic field immunity. The L-shaped slider was levitated as expected by the vibration of the beam, and was moved successfully in both directions by the traveling waves.

1. Introduction

Non-contact linear stages using air pressure or magnetic fields have been studied to achieve highly precise positioning for nano-technology and bio-technology, and other fields. However, the air pressure method requires a lot of pure air, and the apparatus is large. The magnetic system generates a magnetic field which is undesirable for many applications. To overcome these difficulties, we propose in this paper a linear bearing based on Near-Field Acoustic Levitation, which can levitate a planar plate near a vibrating surface. To hold the lateral position of the slider, instead of the planar plate, a beam with an L-shaped cross-section is used as a guide rail, and a slider of the same cross-section is levitated by ultrasonic bending vibrations excited along the beam. This method provides a non-contact linear bearing free from the problems of previous systems. First, the slider was levitated by the standing waves excited along the beam, and the levitation characteristics were studied. Next, the slider's linear motion in both directions due to the excitation of traveling waves by two transducers was measured.

2. Principle and configuration of the L-shaped bearing

Figure 1 shows the configuration of the proposed non-contact linear bearing. A flexural traveling wave is excited along the L cross-section beam, and the slider of the same cross-section is levitated and moved. Due to the L-shaped cross-section, the lateral position of the slider is controlled. Experimental setup is shown in Fig. 2. A 2-m long L-shaped beam was excited using a Langevin transducer with a stepped horn at 18 kHz. The side length and the wall thickness of the beam are 30 mm and 2 mm, respectively. The transducer is mounted diagonally halfway

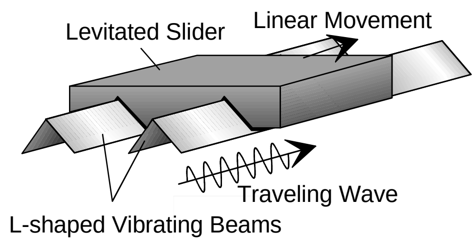


Figure 1 : A non-contact linear bearing using L-shaped vibrating beams.

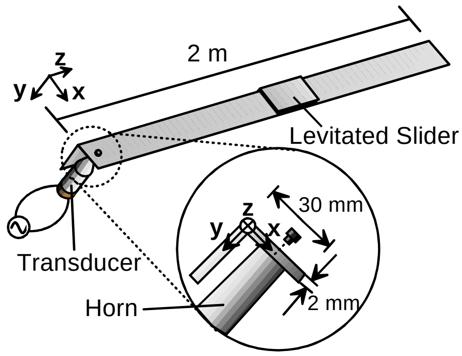
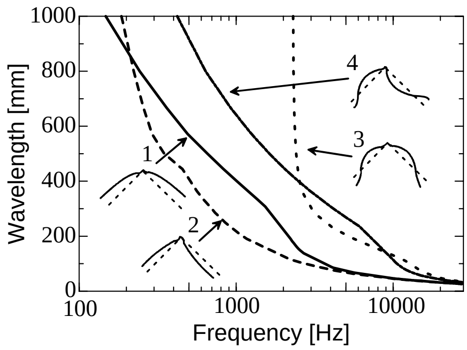
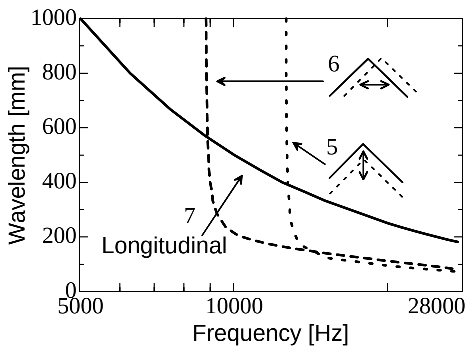


Figure 2 : Experimental setup.



(a) Modes 1, 2, 3, and 4.



(b) Modes 5, 6, and 7.

Figure 3 : Dispersion characteristics of the L-shaped beam calculated by FEM.

from the corner of the L (x = 15 mm), 45 mm from the end of the beam (z = 0). Standing waves are excited since the other end of the L-shaped beam is free in this configuration.

2.1. Dispersion characteristics of the L-shaped beam analyzed by FEM

Prior to the experiments, the dispersion characteristics of the L-shaped beam vibration were analyzed by FEM below 30 kHz. In addition to the longitudinal mode, the horizontally and vertically-polarized bending modes, the higher bending modes, which have a node at the corner of the L-shaped cross-section, can be excited. These higher modes have a larger displacement amplitude, and both the symmetrical and asymmetrical modes exist in both the fundamental and the 2nd modes. The dispersion characteristics of the higher modes from No. 1 to No. 4 and other modes from No. 5 to No. 7 are shown in Fig. 3. Some modes have cut off as demonstrated in the figure.

2.2. The measured vibration modes

The vibration modes in x and y directions at 18 kHz were measured by a laser Doppler vibrometer. Figure 4 shows the results. The vibration modes visualized by the Chladni method is shown in Fig. 5. These modes correspond to mode No. 4 in the analyzed results shown in Fig. 3. The measured wavelength in the z direction was 52 mm, and it was almost equal to the analyzed wavelength of 47 mm.

3. Levitation characteristics by the bending mode standing waves

The slider with the same cross-section (length: 101 mm, mass: 29.7 g) was levitated above the L-shaped beam, and the levitation distance *h* to the displacement amplitude *u* was measured by a laser displacement meter in Fig. 2. The levitation distance was measured as the distance levitated in the vertical direction. The vibration displacement amplitude was measured at the point where it was the largest in the beam. Figure 6 shows the results. The levitation distance *h* to the weight per unit area *w* was measured when a weight was put on the slider, where the displacement amplitude *u* was maintained at 10 μm. The results are summarized in Fig. 7. In the case of the planar beam and the planar slider, the levitation distance is proportional to the displacement amplitude, and inversely proportional to the square root of the weight per unit area independently of the vibration mode[3]. The experimental results of the L-shaped cross-section were slightly different; the levitation dis-

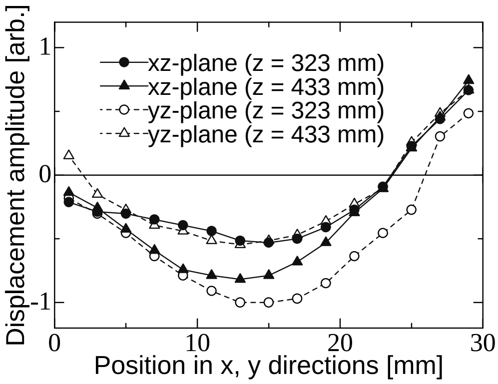


Figure 4 : Measured vibration modes in x, y directions.

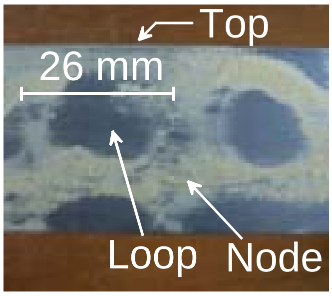


Figure 5 : Chladni figure.

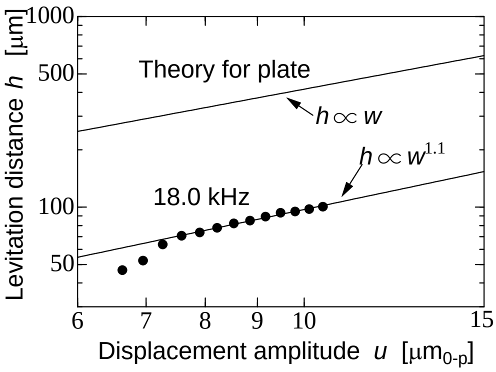


Figure 6 : Levitation distance vs. the displacement amplitude.

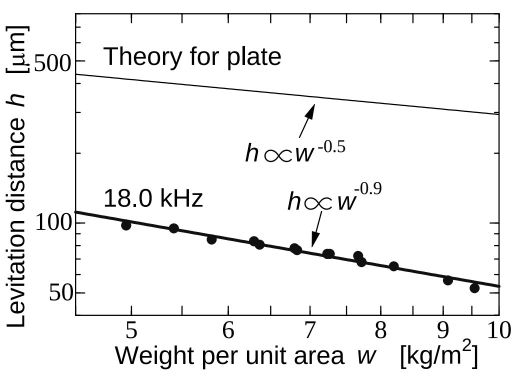


Figure 7 : Levitation distance vs. the weight per unit area.

tance was proportional to the 1.1 power of the displacement amplitude, and to the -0.9 power of the weight per unit area. The value of the levitation distance was almost equal to the measured value for the planar beam. In Fig. 7, levitation rigidity, which is defined as the ratio of the change of the weight per unit area to the levitation distance is shown. The levitation rigidity was 4.3 N/μm/m^2 when the levitation distance was 90 μm, which was about 1/50th the measured value for the planar beam. By extrapolating the result to a levitation distance of 10 μm, the levitation rigidity will become 11.9 kN/μm/m^2. The reason for the difference between the L-shaped and planar beams is the complicated vibration distribution composed of a variety of overlapped modes, and the change of the excitation of the transducer caused by temperature change.

4. Conditions to excite a traveling wave

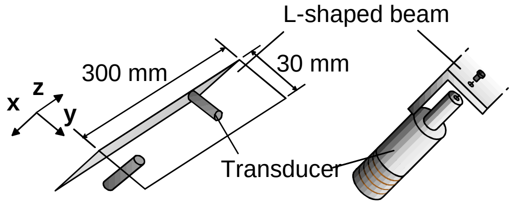
The excitation of a traveling wave by two transducers driven out of phase with each other while mounted on either end of the beam was considered. The driving position on the beam was optimized by FEM analysis for two kinds the mounting methods; (a) diagonal excitation, and (b) vertical excitation as illustrated in Fig. 8. We used a 300 mm long L-shaped aluminium beam driven at 19 kHz in our study.

4.1. Driving position on the beams

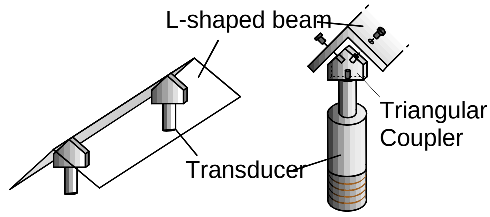
First, the most efficient position to excite a standing wave was explored through FEM calculation for only one transducer. In the case of the diagonal excitation, we found the driving position of y = 15 mm, z = 45 mm to have the maximum displacement amplitude at the corner of the L-shaped cross-section. The second transducer was attached at the symmetrical position of x = 15 mm, z = 45 mm in the z-x plane as shown Fig. 8 (a). The tip of the stepped horn was mounted onto the beam with screws. For vertical excitation, the driving position was found to be z = 37.5 mm where the displacement amplitude at the corner of the L-shaped cross-section was the largest, the second transducer was placed at z = 262.5 mm as shown in Fig. 8 (b). In this case, the horn and the beam were fixed together through a triangular coupler.

4.2. Driven phase difference

The vibration distribution of the beam was analyzed by FEM while varying the driven phase difference between the two transducers. The standing wave ratio (SWR) of the vibration in the z-direction at the corner of the L-shaped cross-section with respect to the driven phase difference is plotted Fig. 9. For diagonal



(a) Diagonal excitation.



(b) Vertical excitation.

Figure 8 : Transducer mounting methods.

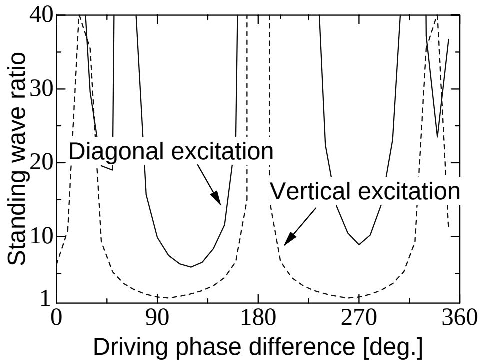


Figure 9 : Standing wave ratio vs. the driving phase difference.

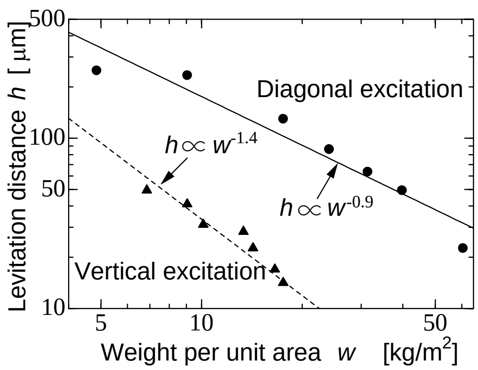


Figure 10 : Levitation distance vs. the weight per unit area.

excitation, the SWR does not change symmetrically with respect to the phase difference of 180° because other modes were excited, and the vibration of the x-z and y-z planes differed. Although a traveling wave with the SWR = 5 could be excited, the slider movement may differ between the forward direction and reverse directions. In vertical excitation, the vibration distribution of the two planes were the same, and the SWR changes symmetrically with respect to a phase difference of 180°. A traveling wave of SWR = 1.7 could be excited in the positive direction at phase difference of 270°, and in the negative direction at a phase difference of 90°, respectively. However, the displacement amplitude was about 1/5 lower than the diagonal excitation.

5. The levitation characteristics via flexural traveling waves

Figure 10 shows the measured levitation distance *h* to the weight per unit area *w* for both diagonal and vertical excitation. A larger maximum displace-ment amplitude was obtained using diagonal excitation; 28 $\mu m_{0\text{-}p}$ in diagonal excitation and 5 $\mu m_{0\text{-}p}$ in vertical excitation. The trend was almost the same as the levitation characteristics by the standing waves. Figure 11 plots the levitation rigidity *k* versus the levitation distance *h* as calculated from Fig. 10. The levitation rigidity *k* was also higher using diagonal excitation. Additionally excited, the difference in vibration modes is related to these results.

6. Measurement of the thrust

The movement of the levitated slider by two transducers driven out of phase each other was experimentally investigated. The value of the thrust acting on the slider was estimated by elevating one end of the beam to equalize the thrust and weight of the slider to stop the slider. Fig. 12 shows the thrust to the maximum displacement amplitude in the diagonal excitation. The thrust was generated successfully in both directions by changing the driving phase difference. A maximum thrust of 1.1 mN was obtained using the displacement amplitude of 28 $\mu m_{0\text{-}p}$. For vertical excitation, the displacement amplitude was smaller compared with diagonal excitation, and the thrust direction was very difficult to control because the boundary conditions of the beam and the transducers differed from the FEM analyzed results.

7. Conclusion

A novel linear bearing based on near field acoustic levitation has been proposed and investigated. A beam with an L-shaped cross-section was used, and the L-shaped slider was levitated as expected. Based on the studies of the driving position on the beam and the conditions to excite a travelling wave, the levitated slider was moved successfully in both directions by the traveling waves. Vertical excitation was found to be inferior to diagonal excitation. A maximum thrust of 1.1 mN was obtained.

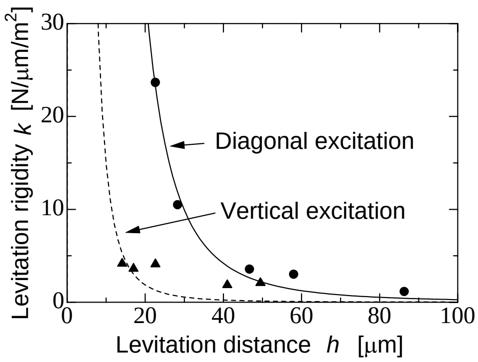


Figure 11 : Levitation rigidity vs. the levitation

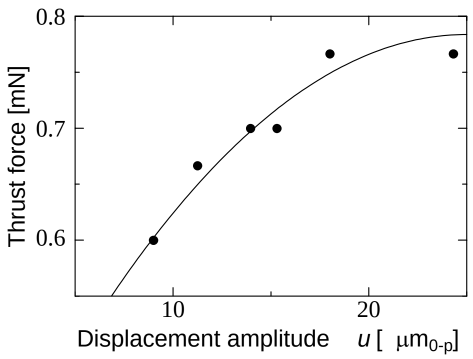


Figure 12 : Thrust vs. the displacement amplitude.

8. References

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