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PHYSICAL FOUNDATIONS OF ENGINEERING ACOUSTICS

Pressure Potential and Stability Analysis in an Acoustical Noncontact Transportation[1]

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Abstract—Near field acoustic traveling wave is one of the most popular principles in noncontact manipulations and transportations. The stability behavior is a key factor in the industrial applications of acoustical noncontact transportation. We present here an in-depth analysis of the transportation stability of a planar object levitated in near field acoustic traveling waves. To more accurately describe the pressure distributions on the radiation surface, a 3D nonlinear traveling wave model is presented. A closed form solution is derived based on the pressure potential to quantitatively calculate the restoring forces and moments under small disturbances. The physical explanations of the effects of fluid inertia and the effects of non-uniform pressure distributions are provided in detail. It is found that a vibration rail with tapered cross section provides more stable transportation than a rail with rectangular cross section. The present study sheds light on the issue of quantitative evaluation of stability in acoustic traveling waves and proposes three main factors that influence the stability: (a) vibration shape, (b) pressure distribution and (c) restoring force/moment. It helps to provide a better understanding of the physics behind the near field acoustic transportation and provide useful design and optimization tools for industrial applications.

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INTRODUCTION

Glass panels in the manufacture of Liquid Crystal Display (LCD) devices are usually handled with direct physical contact. Nowadays the surface area of the glass panel for the purpose of decreasing the manufacturing costs is becoming larger. Besides, the thickness is becoming smaller to minimize the total weight of these devices [1]. In the manipulations of fragile planar objects with large surface areas, the physical contact may give rise to surface scratches and even damages. Moreover, particle generation by a physical contact may cause contamination which is not suitable in the clean room environment. Therefore, the noncontact transportation system is highly demanded in the thin glass panel related manufacturing.

Acoustic radiation pressure is one of the principles used to construct noncontact levitation and transportation systems. Its major advantages lie in no material limitations, system compactness, noninvasiveness to biological objects, absence of particles, as well as considerable load capacity [2–4]. Due to its material independency, acoustic levitation has found a wide spectrum of applications in contactless manipulation of particles and droplets [5–7]. Manipulated objects are ranging from the handling of living cells in a lab-on-a-chip device [8] to air particles of several millimeters [9, 10]. The transportation of planar objects with large surfaces is one of the most interesting challenges in the acoustic levitation field. It has been experimentally demonstrated in several studies, including noncontact linear ultrasonic motor [11], the study on the relationship among levitation height, vibration amplitude, and load surface density for several kinds of vibration modes [12], the transfer and positioning stage using many aligned vibrators [13], and a plate-shaped transporter using flexible posts to minimize the influence of the flexure induced by heavy loads [14]. These observations found that the plates are easy to slip off. But there were no further analysis on this point.

When a body is placed to an acoustic field, the levitation stability determines its dynamic performances. The dynamics of a levitated particle has been tackled by employing the lattice Boltzmann method and viscous fluid [15]. Foresti [16] investigated levitation stability of spherical and ellipsoidal particles in a standing wave field. For a plate with large surface it tends to slip off the radiation surface (rail) due to the non-ideal

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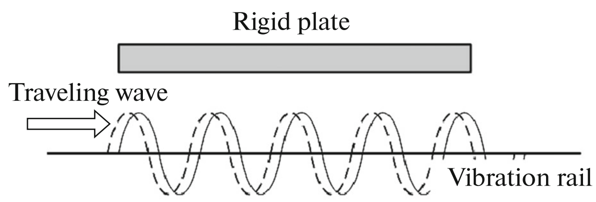

Fig. 1. A schematic diagram of noncontact transportation driven by a flexural traveling wave.

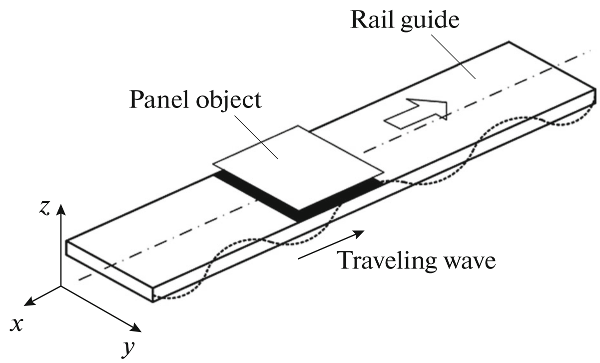

Fig. 2. A schematic view of the experimental setup and the coordinate system.

acoustic field with some disturbances. Experimental observations revealed that levitation and transportation characteristics of panels are strongly influenced by the vibration pattern of the radiation surface, as well as the pressure distribution in the gas film [17]. To obtain a more stable transportation, Ide [18] designed a linear bearing with angular cross section and Ueha [19] presented a T-shape vibrator. Some scientists studied the suspension stability theoretically [20, 21]. They approximated the stability model as a linear mass-spring system with equivalent spring constant. This method can only treat small amplitude of horizontal wobbling and values of stability coefficient were determined by experimental measurements. There still exist open questions regarding the divergent sound field distribution, the centering and orientation effects and restoring moments by inclinations. Therefore, the transportation stability is located at the intersection of acoustics, fluid dynamics, piezoelectricity and structure dynamics. A deeper understanding of the related physics and a quantitative method for stability analysis are needed.

In this regard, we investigate the divergent pressure distribution based on nonlinear traveling wave model with gas inertia for radiation rails with different cross sections. The method of evaluate the stability under small disturbances is provided in details. Both eccentricity and inclination cases are discussed. The restoring forces as well as the restoring moments are calculated based on a time-averaged local potential in nonlinear pressure distributions. Our study validates the previous experiments [12, 20] which demonstrated that a tapered rail provided a more stable transportation. More importantly, our study focuses on the nonlinearity of the equivalent spring coefficient, which has not been addressed in previous models. Our approach provides a useful tool for the design and optimization of the noncontact transportation systems.

NONLINEAR TRAVELING WAVE MODEL

Governing Equations

Consider the case in Fig. 1, where a planar object is levitated and transported by a flexural traveling wave. The acoustic traveling wave is generated by the flexural vibration rail. The gas film between the rigid surface of the plate and the radiation surface of the rail produces two unidirectional forces on the object. One is in the normal direction (z-direction) that levitates the object, the other one is the driving force by the near boundary stream in the horizontal direction (x-direction). There is a velocity gradient in the near boundary stream, and it provides a viscous force which moves the object in the lateral direction. As a result, the panel is levitated against its gravity and gradually accelerated along the rail. Figure 2 shows the schematic view of the experimental setup. The traveling wave flow is a symmetric laminar flow along x-direction, which has the amplitude a and the wavelength λ. The planar object is initially placed at a distance h_0 ($h_0 << \lambda$) from the vibration surface. The traveling wave propagates along the rail guide in the x-direction. At the same time, the rail has its own vibration shape along the width (y-direction). The vibration shape varies by different cross sections. The surface of the rail guide serves as kinematical boundary conditions. Apparently, the pressure distribution is non-uniform in both x- and y-directions. The stability is affected by the pressure distribution especially in y-direction.

It is assumed that the film thickness h is sufficiently small compared with the length and the width of the squeeze film surface. As a result, the pressure gradient along the thickness (z-direction) inside the gas film can be neglected. The momentum equation for the Newtonian fluids with viscous and inertia terms is given by

$$\rho\left(\frac{\partial u_x}{\partial t}+u_x\frac{\partial u_x}{\partial x}+u_y\frac{\partial u_x}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\frac{\partial^2 u_x}{\partial z^2}, \quad (1a)$$

$$\rho\left(\frac{\partial u_y}{\partial t}+u_x\frac{\partial u_y}{\partial x}+u_y\frac{\partial u_y}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\frac{\partial^2 u_y}{\partial z^2}, \quad (1b)$$