A survey of Ultrasonic Waves in Powder Transportation

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Abstract—Ultrasound technology has become an important aspect in material handling and machining. This paper describes the application of standing and traveling ultrasonic waves in powder transportation and how their usefulness in feeding, dosing and supply of small amounts of powder with high accuracy. Piezoelectric actuators have been used to generate the ultrasonic waves in various devices. These devices have presented a unique and simple means of accurate transportation of powder.

Keywords—piezoelectric, powder, transport, ultrasonic waves.

I. INTRODUCTION

A transport system is one of the essential equipment required in various fields of industry and it is important for higher productivity and production automation. In the recent past, powder transportation using ultrasonic vibrations has generated a lot of interest. This has applications in several industrial fields requiring powder handling capability with very accurate mixing processes demanding for an exact control of powder feeding. These industries include food, chemical, pharmaceutical, coating, information and telecommunication industries. There are several distinct methods for powder metering and dispensing: pneumatic methods [1], volumetric dosing, gravimetric dosing, screw and auger dispensers, electrostatic powder metering control, magnetically mediated flow enhancement for controlled powder discharge of cohesive powders, acoustic or ultrasonic controlled powder dispensers and powder feeding devices based on the excitation of a traveling wave in a lossy ultrasonic transmission line [2].
There are three mechanisms for ultrasonic-based transportation: friction driving, wave-action and boundary layer interaction(acoustic streaming) [3].

II. ULTRASONIC WAVES

In general, the human ear is capable of receiving waves having a frequency lying between 15 and 15000 Hz. Below and above this range, mechanical vibrations fail to produce any sensation to the human ear. Though there is no standard limit, the vibrations lying above 15000 Hz are known as ultrasonics. If the velocity of sound waves in air is taken as 331 m/s, then the upper limit of wavelength of ultrasonic waves will be given by [4],

$$\lambda = \frac{v}{f} \tag{1}$$

where λ is the wavelength, v is the velocity and f the frequency.

$$\lambda = \frac{33100}{15000} = 2.2cm \tag{2}$$

The ultrasonic wave (UW) can be generated with the mechanical, electrostatic, electrodynamic, electromagnetic, magnetostrictive effect, piezoelectric effect, and laser methods [5].

A. Traveling Wave

Traveling waves can be produced in infinite systems by forced oscillation with an appropriate phase for the oscillations at the two ends as shown in Figure (1).

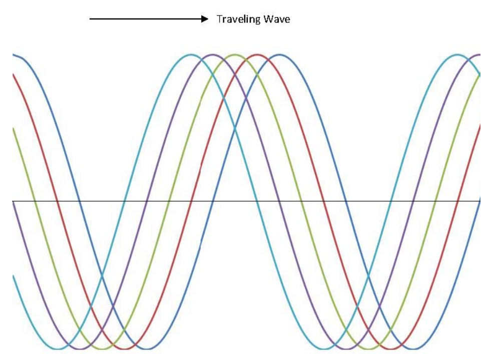

Fig. 1. Traveling wave.

Traveling ultrasonic waves are produced when the reflected rays are dominated by the incident waves. The traveling wave is expressed by

$$u_t(x,t) = A\cos(kx - \omega t) \tag{3}$$

where $u_t(x,t)$ is the traveling wave dislacement, A is the amplitude of vibration, k is a constant, ω is the angular frequency, t is time.

B. Standing Wave

A standing wave is a combination of traveling waves going in opposite directions which are in phase as shown in Figure (2). The standing wave is expressed by

$$u_s(x,t) = A\cos kx \cos \omega t \tag{4}$$

where $u_t(x,t)$ is the standing wave dislacement, A is the amplitude of vibration, k is a constant, ω is the angular frequency, t is time.

Using a trigonometric relation, equation (3) can be transformed to

$$u_t(x,t) = A\cos kx \cos \omega t + A\cos(kx - \frac{\pi}{2})\cos(\omega t - \frac{\pi}{2}) \tag{5}$$

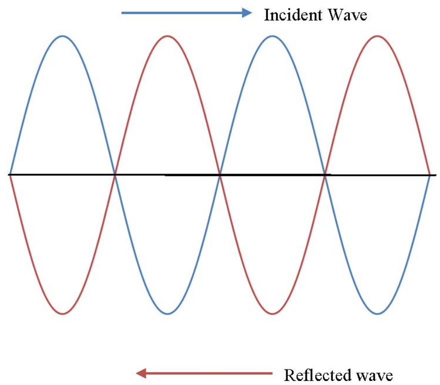

Fig. 2. Traveling wave.

From equations 4 and 5, a traveling wave can be generated by superimposing two standing waves whose phases differ by $90°$ from each other both in time and in space. This principle is necessary to generate a traveling wave on a limited volume/size substance, because only standing waves can be excited stably in a finite size [6].

III. ULTRASONIC POWDER TRANSPORTATION SYSTEMS

A. Standing Wave systems

Standing ultrasonic waves have been explored for powder transportation. In an acoustic standing-wave field, it is well known that objects smaller than the wavelength can be trapped at antinodes of the pressure field [7] as shown in Figure (3).

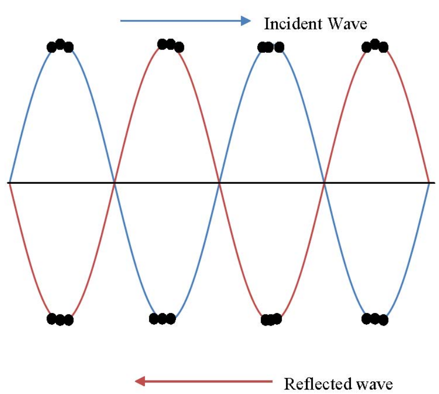

Fig. 3. Particles trapping at the antinodes of standing waves.

When a reflector is set in front of a transducer, the incident wave and the reflected wave generate a standing wave field as shown in figure (4). In this field, most of the solid particles receive acoustic radiation pressure which pushes them toward nodes in the sound pressure distribution formed every half wavelength along the sound beam. In the direction normal to the sound beam axis, the particles are pushed toward the axis. It was possible to transport the particles by changing the driving frequency. However, the moving direction and the transportation distance are different depending on the distance from the reflector [8]

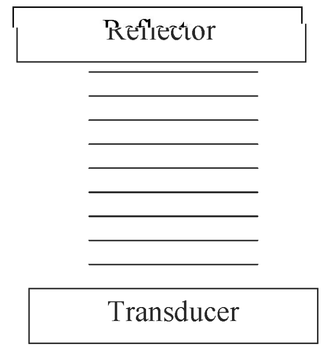

Fig. 4. Generation of a standing wave field using a reflector.

A device has been developed where a standing wave field is generating by two transducers whose sound beam axes cross each other without using a reflector as shown in Figure (5). The sound field does not resonate since the sound beams do not return to each transducer. When a particle was put in the region of the crossing sound beams, it was trapped at nodes of the sound pressure. By changing the phase difference between the transducers, the trapped position shifted, and transportation of the particle occurred. In addition, by assigning slightly different frequency to each transducer, transportation at constant speed was realized. However, it was difficult to manipulate the particle at larger inclination angles of the sound beams. The sound field generated by crossing sound beams was obtained using a theoretical analysis. The sound pressure produced by a piston source in an infinite rigid wall can be expressed by the following Rayleigh's formula [9]:

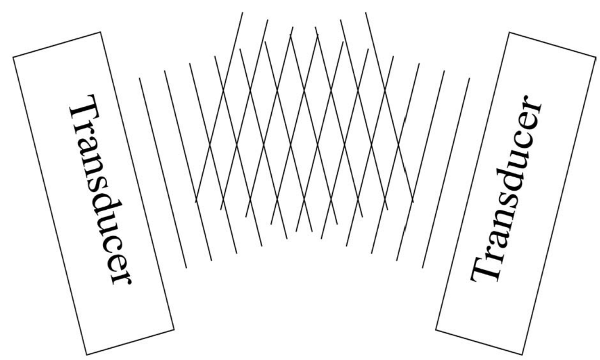

Fig. 5. Generation of a standing wave field using two crossing sound beams.

$$p = j\frac{\rho c \mathrm{V}_0}{\lambda}\exp(j\omega t)\int\int_F \frac{exp(-jkr)}{r}dF \tag{6}$$

where V_0, is vibrating velocity at the sound source, ρ is density of the medium, c is sound speed, λ is the wavelength, ω is angular frequency, k is ω/c, and r is the distance between an arbitrary point on the transducer and the observation point.

An ultrasonic powder transportation device which consists of a pair of phase shifted bending vibrators facing each other across a gap has been developed as shown in Figure (6). The upper vibrator of the device is laterally shifted relative to the lower one by a quarter wavelength of the bending mode and the two vibrators are driven in temporal phases different from each other by $90°$. In such a condition, powder is transported in one direction through the gap [10]. The transportation is most effective when the bending vibration, i.e. the lowest-order flexural mode of Lamb waves is phase matched to ultrasound in the air and the unidirectional ultrasound is raidated along the plates.

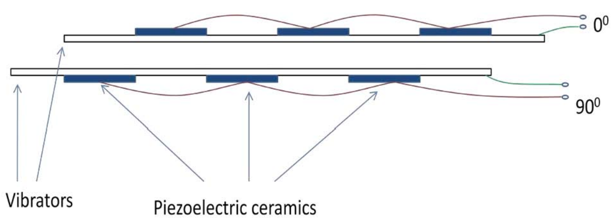

Fig. 6. An ultrasonic powder transportation device consisting of a pair of phase shifted bending vibrators facing each other.

B. Traveling Wave Systems

There have been two ways of generating progressive waves on the finite length of an elastic beam. One is through impedance matching using transmission theory, and the other is through two-mode excitation, in which two neighboring natural mode shapes are excited by forces with the same frequency but at a phase difference of $90°$. It is rather difficult to efficiently perform the impedance matching in an ultrasonic transmission line because the impedance of the piezoelectric actuator changes with the load and the excitation frequency. Also, in a typical factory environment, it is necessary to change the transport speed and the direction of motion, which would be controlled through the computer. The impedance matching method involves two switches and a circuit to manually change the direction of motion. Because hundreds of volts are supplied to the piezoelectric actuators, interface with the computer is not an easy task. By using two-mode excitation, the transport speed and the direction of motion can be controlled instead by changing the magnitude and phase relationships of supplied voltage. With a function synthesizer having computer interface capability, this can be accomplished readily [11].

A schematic drawing of the microactuator is shown in Figure (7). The microactuator is composed of a stator and slider. The stator consists of two piezoelectric ceramic (PZT) tubes and one elastic pipe, which can be regarded as a bridge connecting the two PZT tubes. The elastic material is a thin film metallic glass (TFMG), which is an ideal material for microelectromechanical systems (MEMS) and other micro elastic structures. When high frequency harmonic voltages are applied, PZT tubes vibrate based on the converse piezoelectric effect. The TFMG pipe usually vibrates as a standing wave at its eigenmode under the excitation of the PZT vibration. At some specific driving signals and under suitable boundary conditions, however, a traveling wave is generated on the TFMG pipe to drive the slider, which is a stainless pipe with high precision, to move in two directions [12].

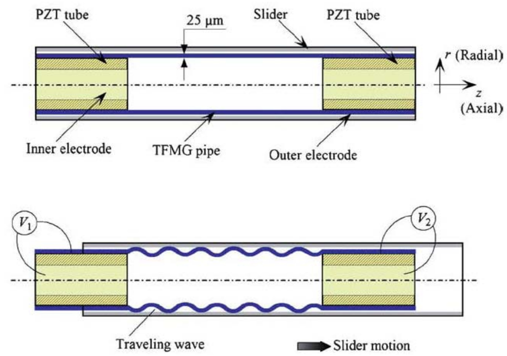

Fig. 7. Generation of traveling Wave in Piezoelectric Ultrasonic Bidirectional Linear Microactuator.

A powder feeding device [13] with a transmission line consisting of an acrylic pipe has been developed, with the set up shown in Figure (8).

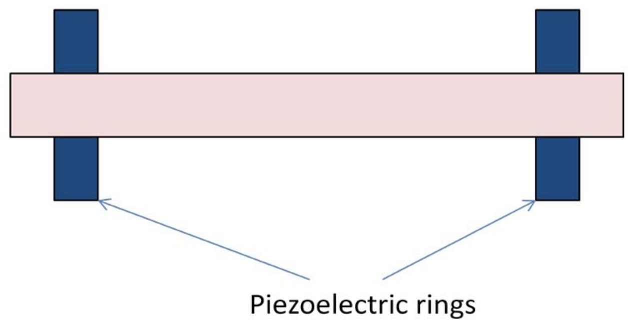

Fig. 8. A traveling wave powder transportation device using two transducers.

The axisymmetric wave is excited by the piezoelectric ceramic disk vibrating in the first radial mode. The progressive wave was generated even without giving attention to acoustic matching at the receiving end due to the use of a lossy transmission line. This is due to the fact that the reflected wave reduces in magnitude leaving the incident wave from the transducer as the dominant wave.

A trial device for transporting small amounts of powder has been developed using a lossy transmission material namely acrylic pipe and only one transducer as in Figure (9).

The device was used to move powder placed inside the pipe forward. During interference of the incident and the reflected waves, the incident waves became dominant producing a traveling wave. The particles on the inside of the pipe wall were moved forward through the resulting elliptical movement of the surface area points [14].

C. Ultrasonic Motors(USM)

Ultrasonic motor (USM) is a typical device driven by ultrasonic induced friction. In the USM, the rotor is driven by frictional forces between the rotor and stator. The frictional force is generated by the ultrasonic wave travelling or standing in the stator of USM [3].

The principle of the USM is as follows: A particle at the surface of a transmission bar in which a flexural traveling

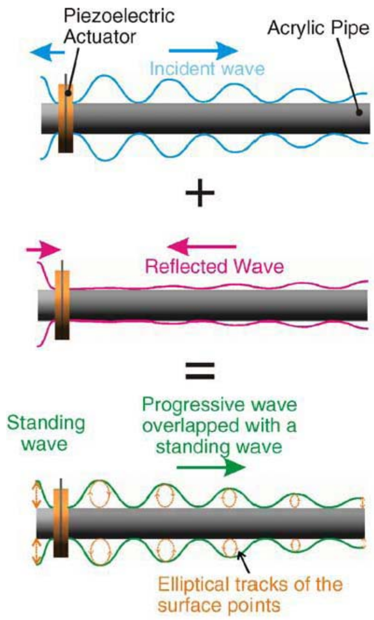

Fig. 9. Traveling wave in an acrylic pipe

wave is guided, moves elliptically. If a movable object is in contact with the bar, the object is forced to move through frictional force. In order to obtain the traveling wave, a pair of longitudinal vibrators are connected to the transmission bar. In this system, one of the vibrators excites a flexural wave in the bar and the other absorbs it [15].

The device shown in Figure (10) consists of a beam and modules that contain piezoelectric actuators and horns [11].

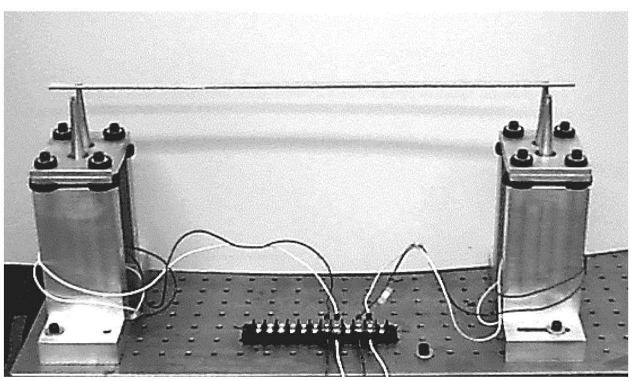

Fig. 10. An object transport system using flexural ultrasonic waves.

The two modules are supplied with sinusoidal voltages of the same frequency but a phase difference of $90°$. When the beam is excited, there are two traveling waves on the beam. Witht the excitation of 27.1 kHz, which is a median of 30^{th} and 31^{st} natural frequencies, two progressive waves propagating in opposite directions cancel each other, resulting in standing waves. Below or above 27.1 kHz, one wave is excited more than the other. The resulting waves propagate in the same direction as the waves with the greater amplitude propagate.
A linear-type ultrasonic piezoelectric actuator [16] with a traveling wave has been constructed. The principle of this actuator is as follows: A particle at the surface of a transmission bar, in which a flexural traveling wave is guided, moves elliptically. If a movable object is in contact with the bar, the object is forced to move through friction force. The intuitive analogy may be "a surfboard on a wave". In the device in Figure (11), the traveling wave was synthesized by supplying two-phase high-frequency electricity to the piezoelectric elements attached to the copper bar.

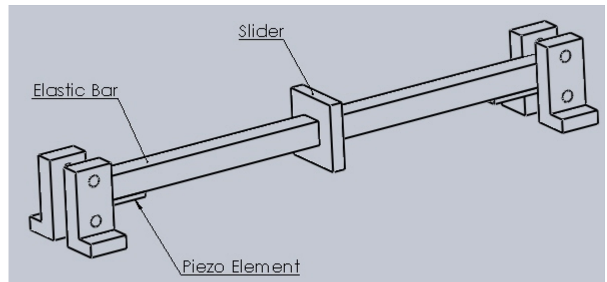

Fig. 11. An object transport system using flexural ultrasonic waves.

IV. Conclusion

The ultrasonic technology of transporting powder have showed that it is possible to feed small amounts of powder with high quantitative accuracy. These ultrasonic devices are used with low voltage and are ideal for miniaturisation. Other advantages of standing wave and traveling wave principle of transporting powder are:

1) Simple mechanical structure
2) Low power consumption
3) No wear, simple maintenance
4) Vacuum and clean room compatibility
5) Operation at cryogenic temperatures is possible

In addition, Ultrasonic motors have the following merits.

1) Low speed and high torquedirect drive.
2) Quick response, wide velocity range, hard brake and no backlash: excellent controllability; fine position resolution.
3) High power/weight ratio and high efficiency.
4) Quiet drive.
5) Compact size and light weight.
6) Simple structure and easy production process.
7) Negligible effect from external magnetic or radioactive fields, and also no generation of these fields.

However, these systems have some drawbacks;

1) Necessity for a high frequency power supply.
2) In the case of motors, there is less durability due to frictional drive.
3) Drooping torque$-$speed characteristics.

Due to the merits of these systems, more research needs to be carried out on non-contact means of powder transportation inorder to improve the design and functionality of the existing systems or even develop better designs.

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