Matrix Method for Acoustic Levitation Simulation

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Abstract—A matrix method is presented for simulating acoustic levitators. A typical acoustic levitator consists of an ultrasonic transducer and a reflector. The matrix method is used to determine the potential for acoustic radiation force that acts on a small sphere in the standing wave field produced by the levitator. The method is based on the Rayleigh integral and it takes into account the multiple reflections that occur between the transducer and the reflector. The potential for acoustic radiation force obtained by the matrix method is validated by comparing the matrix method results with those obtained by the finite element method when using an axisymmetric model of a single-axis acoustic levitator. After validation, the method is applied in the simulation of a noncontact manipulation system consisting of two 37.9-kHz Langevin-type transducers and a plane reflector. The manipulation system allows control of the horizontal position of a small levitated sphere from −6 mm to 6 mm, which is done by changing the phase difference between the two transducers. The horizontal position of the sphere predicted by the matrix method agrees with the horizontal positions measured experimentally with a charge-coupled device camera. The main advantage of the matrix method is that it allows simulation of non-symmetric acoustic levitators without requiring much computational effort.

I. INTRODUCTION

NONCONTACT handling of materials and substances is required in chemical analysis, biotechnology and manufacturing processes of semiconductor devices. Different noncontact techniques have been proposed to levitate particles, including magnetic [1], electrostatic [2], [3], optical [4], aerodynamic [5], and acoustic levitation [6]. When compared with the electrostatic and optical techniques, the acoustic levitation technique does not require any special property of the levitated material, such as its electric or magnetic properties. The main advantage of acoustic levitation over aerodynamic levitation is that it does not require any external pressurized air supply, air filters, or air tubes.

A typical design of an acoustic levitator, often referred to as single-axis, consists of a Langevin-type transducer and a circular reflector, which are ideally separated by a distance equal to a multiple of half the wavelength. This type of levitator, a standing wave is generated between the transducer and the reflector, and particles that are small compared with the wavelength can be levitated at the pressure nodes. Because this type of levitator has radial symmetry, axisymmetric numerical models can be used to reduce the computational time. The numerical modeling of single-axis acoustic levitators using axisymmetric numerical models has been presented by some authors. Xie and Wei have used the axisymmetric boundary integral and it takes into account the multiple reflections that occur between the transducer and the reflector. The potential for acoustic radiation force obtained by the matrix method is validated by comparing its results with those obtained by the finite element method when using an axisymmetric model of a single-axis acoustic levitator. After validation, the method is applied in the simulation of a noncontact manipulation system consisting of two 37.9-kHz Langevin-type transducers and a plane reflector. The manipulation system allows control of the horizontal position of a small levitated sphere from −6 mm to 6 mm, which is done by changing the phase difference between the two transducers. The horizontal position of the sphere predicted by the matrix method agrees with the horizontal positions measured experimentally with a charge-coupled device camera. The main advantage of the matrix method is that it allows simulation of non-symmetric acoustic levitators without requiring much computational effort.

Recently, some authors proposed new types of levitators without radial symmetry. Hu and collaborators have worked on a π-shaped ultrasonic transducer for manipulating small particles [11], [12] and Koyama and Nakamura proposed a new concept of object transportation using acoustic levitation [13], [14]. According to this new concept, conveyor belts used in modern industry could be replaced by a noncontact transportation system, composed of linear transporters [13] and circular transporters [14]. Because these new types of levitators do not have a circular symmetry, their analysis requires three-dimensional finite element models, which considerably increase the computational cost because of the large number of elements.

To reduce the simulation computational time of non-radial symmetry levitators, this work uses a matrix method based on the monochromatic transfer matrix (MTM) [15] method to determine the potential for acoustic radiation force in the region between the transducer and the reflector. This method is based on the Rayleigh integral and it was previously used to determine the continuous wave acoustic field generated by an array through a soft curved interface [16]. The modeling of an acoustic levitator by using the Rayleigh integral with multiple reflected waves between the transducer and the reflector was proposed by Kozuka and collaborators [17], [18]. In this work, the numerical model proposed by Kozuka and the MTM method are combined to create a new numerical method able to simulate acoustic levitators with non-radial symmetry. The method is validated by comparing its results with those obtained by the finite element method of a
single-axis acoustic levitator. After validation, the method is applied to the modeling of a noncontact transportation system composed of two circular transducers and a plane reflector.

II. DESCRIPTION OF THE MATRIX METHOD

The numerical method presented in this section is used to determine the potential for acoustic radiation force in an acoustic levitator composed of only one transducer and one reflector. However, the method can be easily modified to include more transducers and reflectors. The first step in determining the potential for acoustic radiation force that acts on a small sphere is to calculate the pressure field in the region between the transducer and the reflector, which is given by the Rayleigh integral. Numerically, the Rayleigh integral is determined by discretizing the transducer and the reflector surfaces in small area cells, as shown in Fig. 1. According to Fig. 1, the transducer radiating surface is discretized in \( N \) small cells of area \( s_n \) and the reflector is divided into \( I \) cells of area \( s_i \). Subscripts \( n \) and \( i \) correspond to the cell number on the transducer and reflector faces, respectively. The distance between cells \( s_i \) and \( s_n \) are denoted by \( r_{in} \). The distances between center \( s_i \) and measurement point \( m \) and \( s_n \) and point \( m \), are represented by \( r_{im} \) and \( r_{nm} \), respectively. Given the transducer face and reflector geometries, the problem consists of determining the acoustic pressure in a set of measurement points \( m \), which are located in the region between the transducer and the reflector. The total number of measurement points is \( M \).

Considering that each point of the transducer face vibrates harmonically, the displacement of each cell \( s_n \) is represented by the complex amplitude \( U_n \). The modulus of \( U_n \) represents the amplitude, and the phase of \( U_n \) corresponds to the excitation phase of each cell. To determine the acoustic pressure at the points \( m \), it is necessary to take into account the many reflections that occur between the transducer and the reflector, which is done through the multiplication of the transfer matrices \( T^{(TR)}, T^{(RT)}, T^{(TM)}, \) and \( T^{(RM)} \). The matrices \( T^{(TR)}, T^{(RT)}, T^{(TM)}, \) and \( T^{(RM)} \) represent the transfer matrices from the transducer to the reflector, reflector to the transducer, transducer to the measurement points, and reflector to the measurement points, respectively. Disregarding the reflections between the transducer and reflector, the direct acoustic pressure at point \( m \) generated by the transducer is given by

\[
\begin{bmatrix}
    p_1 \\
    p_2 \\
    \vdots \\
    p_M
\end{bmatrix}
= \frac{\omega \rho c}{\lambda}
\begin{bmatrix}
    T_{11}^{(TM)} & T_{12}^{(TM)} & \cdots & T_{1N}^{(TM)} \\
    T_{21}^{(TM)} & T_{22}^{(TM)} & \cdots & T_{2N}^{(TM)} \\
    \vdots & \vdots & \ddots & \vdots \\
    T_{M1}^{(TM)} & T_{M2}^{(TM)} & \cdots & T_{MN}^{(TM)}
\end{bmatrix}
\begin{bmatrix}
    U_1 \\
    U_2 \\
    \vdots \\
    U_N
\end{bmatrix},
\]

where \( P = [p_1, p_2, \ldots, p_M]^T \) is a vector whose components are the acoustic pressure at each point \( m \), \( \omega \) is the angular frequency, \( \rho \) is the density of the propagation medium, \( c \) is the wave propagation velocity, \( \lambda \) is the wavelength, and the elements of matrix \( T^{(TM)} \) are given by [15], [16]

\[
T_{mn}^{(TM)} = s_n \frac{\exp(-jkr_{nm})}{r_{nm}},
\]

where \( k = \omega/c \) is the wavenumber and \( j = \sqrt{-1} \). The acoustic pressure given by (1) is equivalent to the Rayleigh integral. The constant \( \omega \rho c/\lambda \) that multiplies the matrix \( T^{(TM)} \) in (1) should be used when the transducer is emitting the acoustic wave. When the acoustic wave reaches the transducer, it is reflected, and the constant \( \omega \rho c/\lambda \) should be replaced by \( j/\lambda \) [17], [18]. The multiple reflections that occur in an acoustic levitator are considered in the model by adding the reflection terms to (1):

\[
P = \left( \frac{\omega \rho c}{\lambda} \right) T^{(TM)} U + \left( \frac{\omega \rho c}{\lambda} \right) \left( \frac{j}{\lambda} \right)^2 T^{(RM)} T^{(TR)} U
+ \left( \frac{\omega \rho c}{\lambda} \right) \left( \frac{j}{\lambda} \right)^3 T^{(TR)} T^{(RT)} T^{(TR)} U
+ \left( \frac{\omega \rho c}{\lambda} \right) \left( \frac{j}{\lambda} \right)^4 T^{(RM)} T^{(TR)} T^{(TR)} T^{(TR)} U + \ldots.
\]

The first term on the right-hand side of (3) corresponds to the direct pressure field emitted by the transducer. The second term corresponds to the wave emitted by the transducer and reflected by the reflector. The other terms correspond to the other multiple reflections in the levitator. Eq. (3) is equivalent to the numerical model proposed by Kozuka and collaborators [17], [18], in which the multiple reflections are considered by using many Rayleigh integrals. Matrices \( T^{(TR)}, T^{(RT)}, \) and \( T^{(RM)} \) are very similar to \( T^{(TM)} \) in (2) and they are given by

\[
T_{in}^{(TR)} = s_n \frac{\exp(-jkr_{im})}{r_{im}}
\]

\[
T_{mi}^{(RT)} = s_i \frac{\exp(-jkr_{im})}{r_{im}}
\]

\[
T_{mi}^{(RM)} = s_i \frac{\exp(-jkr_{im})}{r_{im}}.
\]
After obtaining the pressure field in the region between the transducer and the reflector, the Gor’kov theory [10] is used to obtain the potential for acoustic radiation force that acts on a small sphere, which is assumed to be much smaller than the wavelength. According to Gor’kov theory, the acoustic radiation potential $V$ that acts on a small sphere of radius $R$ is given by

$$V = 2\pi R^3 \left( \frac{p^2}{3\rho c^2} - \frac{\rho \dot{u}^2}{2} \right),$$

(7)

where $p^2$ and $\dot{u}^2$ are the mean square amplitudes of the pressure and velocity, respectively. The velocity field can be obtained from the pressure field through the following equations [19]:

$$\phi = -\frac{\rho}{j\omega p}$$

(8)

$$\dot{u} = \nabla \phi,$$

(9)

where $\phi$ is called the velocity potential. To obtain a potential for acoustic radiation force that is independent of the particle radius, a relative acoustic potential $\tilde{V}$ is defined:

$$\tilde{V} = \frac{V}{2\pi R^3}.$$  

(10)

To exemplify the matrix method, the relative acoustic radiation potential in an acoustic levitator consisting of a 10-mm-diameter circular ultrasonic transducer and a 40-mm-diameter plane reflector is determined by using the Matlab software (The MathWorks, Natick, MA). In this example, the transducer vibrating surface vibrates harmonically with $1 \mu m$ displacement amplitude and a frequency of 20 kHz. The transducer is used to generate a standing wave in the air region between the transducer and the reflector. The distance between the transducer and reflector is 18 mm, which was obtained by performing a simulation of the scanning of the resonance. The procedure used to obtain this distance is presented in [9]. The sound velocity in air is 340 m/s and its density is 1.2 kg/m$^3$. Before determining the potential for acoustic radiation force, it is necessary to determine the pressure field in the air region, which is given by (3). The real part of the acoustic pressure determined by the matrix method is presented in Fig. 2(d). In this example, the pressure field was determined by considering the first 6 terms of the right-hand side of (3) and both transducer and reflector faces were discretized in $1 \times 1$ mm square elements. Figs. 2(a), 2(b), and 2(c) show, respectively, the real part of the first, second, and third terms of the right-hand side of (3). As shown in these figures, the amplitude of the acoustic pressure in the region between the transducer and reflector rapidly decreases to zero as the number of the reflection term of (3) increases. This decrease of the peak-to-peak acoustic pressure as a function of the reflection term is shown in Fig. 3. The peak-to-peak acoustic pressure of Fig. 3 was determined over the domain $-18 \text{ mm} < z < 0 \text{ mm}, -20 \text{ mm} < x < 20 \text{ mm}$. This figure shows that 6 reflection terms are sufficient to model an acoustic levitator consisting of a plane radiating surface transducer and a plane reflector.

After determining the pressure field, the relative acoustic potential that acts on a small sphere is calculated. First, the pressure field is replaced in (8) and (9) to determine the velocity field, and then, the pressure and velocity fields are replaced in (7) to determine the acoustic

![Fig. 2. Real part of the acoustic pressure in a levitator consisting of a 10-mm-diameter transducer and a 40-mm-diameter reflector: (a) direct pressure emitted by the transducer; (b) wave emitted by the transducer and reflected by the reflector; (c) wave emitted by the transducer and reflected by the reflector and the transducer; (d) acoustic pressure considering the multiple reflections between the transducer and reflector.](image-url)
radiation potential. Finally, the relative acoustic radiation potential is determined through (10), and it is presented in Fig. 4. The positions of minimum acoustic potential are denoted by the symbol “+” in Fig. 4. These points correspond to the positions where small particles can be levitated.

III. Validation by the Finite Element Method

In this section, the matrix method used to determine the potential for acoustic radiation force is validated by comparing its results with those obtained by the finite element method. Several authors have shown that an acoustic levitator can be correctly modeled by using the finite element method [9], [13], [14], [20]. Therefore, this method was chosen to validate the proposed numerical algorithm. Here, the analysis of acoustic levitators by using the finite element method is performed with the commercial package ANSYS (ANSYS Inc., Canonsburg, PA). To reduce the computational time required by the finite element method, the validation is performed in levitators with axisymmetric geometry. In ANSYS, three different types of elements are used to simulate the acoustic levitator. The transducer and reflector are modeled by using a 2-D axisymmetric structural element (PLANE42) with degrees of freedom of displacements in directions \(x\) and \(z\). The modeling of the air region is conducted by using a 2-D acoustic fluid element (FLUID29 with no structure present) and the interface between the transducer and the air, and between the reflector and the air is simulated by using a fluid element with fluid-structure interface (FLUID29 with structure present). The acoustic fluid element with no structure has a pressure degree of freedom and the coupling between this element and the structural elements of the transducer is performed by the fluid-structure element that has displacement and pressure degrees of freedom.

The modeling of an acoustic levitator by the finite element method is shown in Fig. 5. In this figure, direction \(x\) corresponds to the radial direction. In the finite element model, no reflection boundary conditions are applied to simulate an infinite extent of air.

The method validation is conducted by simulating two configurations of acoustic levitators. First, the validation is performed in a levitator consisting of a transducer with a plane radiating surface and a plane reflector. Then the validation is extended to a levitator consisting of a plane radiating surface transducer and a concave reflector.

A. Levitator With a Plane-Faced Transducer and a Plane Reflector

The method validation for a levitator consisting of a plane-faced transducer and a plane reflector is conducted for three different transducer radii (5, 10, and 15 mm). The reflector radius remains constant at 20 mm. The distance between the transducer and the reflector is 18 mm.
and the transducer vibrates harmonically at 20 kHz with a displacement amplitude of 1 μm. In ANSYS, a mesh size of 0.125 mm is used in all simulations. In the matrix method, both transducer and reflector are discretized in 1-mm-size elements and 6 terms on the right-hand side of (3) were used to determine the relative acoustic potential. The comparison between the relative acoustic potential obtained by the finite element method and the matrix method is presented in Fig. 6 for the three different values of radius, and the relative acoustic potential comparison along the $z$ axis is presented in Fig. 7. There is a good agreement between the results obtained by the finite element method and by the matrix method. In Fig. 6, the levitation positions are indicated by the symbol “+” for both methods.

**B. Levitator With a Plane-Faced Transducer and a Concave Reflector**

After validating the numerical method for acoustic levitators consisting of a plane-faced transducer and a plane reflector, the method is verified for an acoustic levitator consisting of a plane-faced transducer and a concave reflector. In a levitator consisting of a plane reflector and

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**Fig. 6.** Comparison between the relative acoustic potential determined by the matrix method and by the finite element method: (a) matrix method (transducer radius = 5 mm), (b) finite element method (transducer radius = 5 mm); (c) matrix method (transducer radius = 10 mm), (d) finite element method (transducer radius = 10 mm); (e) matrix method (transducer radius = 15 mm), (f) finite element method (transducer radius = 15 mm).

**Fig. 7.** Comparison between the relative acoustic potential determined by the matrix method and by the finite element method along the $z$ axis: (a) transducer radius = 5 mm, (b) transducer radius = 10 mm, (c) transducer radius = 15 mm.
a plane transducer, only 6 terms on the right-hand side of (3) are needed to correctly determine the potential for acoustic radiation force. In this type of levitator, the wave emitted by the transducer is rapidly dispersed in the environment after few reflections. However, in a levitator consisting of a plane transducer and a concave reflector, more reflections occur between the transducer and the reflector, before being dispersed into the environment. The peak-to-peak acoustic pressure between the transducer and the reflector as a function of the reflection term of (3) is presented in Fig. 8 for two different acoustic levitators. The peak-to-peak acoustic pressure of Fig. 8 was determined over the domain \(-19 \text{ mm} < z < 0 \text{ mm}, -20 \text{ mm} < x < 20 \text{ mm}\). Fig. 8(a) presents the peak-to-peak acoustic pressure of an acoustic levitator consisting of a 10-mm-diameter plane-faced transducer and a 40-mm-diameter concave reflector with a curvature radius of 70 mm. The levitator of Fig. 8(b) consists of a 20-mm-diameter plane-faced transducer and a 40-mm-diameter concave reflector with a curvature radius of 50 mm. In both levitators, the distance between the transducer and the reflector is 19 mm, which was obtained by performing a scanning of the resonance. Even though both levitators have concave reflectors, the convergence rate of Fig. 8(a) is much faster than that of Fig 8(b). In the levitator of Fig. 8(a), only 6 terms are sufficient to correctly describe the levitator behavior, and in Fig. 8(b), it is necessary to consider 20 or more terms on the right-hand side of (3). This difference in the convergence rate can be explained by two factors. One is the transducer directivity and the other is the reflector curvature radius. Because the transducer diameter in Fig. 8(b) is greater than the transducer in Fig. 8(a), it has a higher directivity, and consequently, the wave emitted by it takes more time to be dispersed into the environment than is the case in Fig. 8(a). The other factor accounting for a slow convergence rate is the reflector curvature radius. Because the reflector curvature radius in Fig. 8(b) is higher than that in Fig. 8(a), the wave is reflected many times before it is completely dispersed into the environment.

The comparison between the relative acoustic potential determined by the matrix method and by the finite element method for two different acoustic levitators is presented in Fig. 9 and the acoustic potential along the z axis is presented in Fig. 10. In both figures, there is a good agreement between the acoustic potentials determined by the finite element method and by the matrix method.

IV. Simulation of a Noncontact Manipulation System

Typically, acoustic levitation has been used to trap particles at the pressure nodes of a standing wave field. Recently, new acoustic techniques have been proposed not only to trap particles at a fixed position, but also to transport small particles [13], [14], [21], [22]. In these techniques, the transport of particles is performed by gradually changing the positions of the pressure nodes. There are different ways to change the position of a pressure node, such as translating the transducer or the reflector [22] or by controlling the phase difference between two transducers [13], [21].

In this section, the proposed numerical method is applied to the modeling of a noncontact manipulation system consisting of two 20-mm-diameter Langevin-type transducers and a plane reflector, as shown in Fig. 11. Each transducer has a resonance frequency of 37.9 kHz. The particle manipulation is conducted by controlling the phase difference between the two transducers. In the numerical model of the noncontact manipulation system, the transducers and the reflector are discretized in 0.75-mm-size elements.
The matrix model is used to determine the potential for acoustic radiation force in the measurement plane of Fig. 11. The measurement plane of Fig. 11 has dimensions of $40 \times 24$ mm, and consists of 3969 measurement points, with a spacing of 0.5 mm. The pressure field $P_1$ generated by transducer 1 at the measurement plane is given by

$$P_1 = \left( \frac{\omega p c}{\lambda} \right) T^{(TM)} U_1 + \left( \frac{\omega p c}{\lambda} \right) \left( \frac{j}{\lambda} \right) T^{(RM)} T^{(TR)} U_1$$

$$+ \left( \frac{\omega p c}{\lambda} \right) \left( \frac{j}{\lambda} \right)^2 T^{(2TM)} T^{(R2T)} T^{(TR)} U_1$$

$$+ \left( \frac{\omega p c}{\lambda} \right) \left( \frac{j}{\lambda} \right)^3 T^{(RM)} T^{(2TR)} T^{(R2T)} T^{(TR)} U_1$$

$$+ \left( \frac{\omega p c}{\lambda} \right) \left( \frac{j}{\lambda} \right)^4 T^{(2TM)} T^{(R2T)} T^{(2TR)} T^{(TR)} T^{(TR)} U_1 + \cdots .$$

The first term on the right-hand side of (11) corresponds to the direct pressure field emitted by transducer 1 and the second term corresponds to the pressure field emitted by transducer 1 and reflected by the plane reflector. The third term of the right-hand side of (11) considers that the wave reflected by the reflector will arrive at transducers 1 and 2 and it will be reflected again by both transducers. In (11), the superscript $2T$ means that both transducers are considered and the superscript $T_1$ means that only transducer 1 is considered. According to this definition, the matrices $T^{(2TM)}$, $T^{(R2T)}$, $T^{(2TR)}$, and $T^{(TR)}$ represent the transfer matrices from transducers 1 and 2 to the measurement points, reflector to transducers 1 and 2, transducers 1 and 2 to the reflector, and transducer 1 to
the reflector, respectively. Because the transducers used in the noncontact manipulation system have a high directivity, it was not considered in (11) that the wave emitted by transducer 1 is reflected by transducer 2. If the transducer has a low directivity, it is necessary to include the multiple reflections terms that can occur between transducers 1 and 2. Similarly to (11), the pressure field $P_2$ generated by transducer 2 is given by:

![Fig. 12. Comparison between the numerical acoustic radiation potential and the levitation position of a small styrofoam sphere for different values of phase difference between transducers 1 and 2: (a) experimental ($\phi = -180^\circ$), (b) numerical ($\phi = -180^\circ$); (c) experimental ($\phi = 0^\circ$), (d) numerical ($\phi = 0^\circ$); (e) experimental ($\phi = +60^\circ$), (f) numerical ($\phi = +60^\circ$); (g) experimental ($\phi = +180^\circ$), (h) numerical ($\phi = +180^\circ$).]
\[ P_2 = \left( \frac{\omega \rho c}{\lambda} \right) T^{(T\lambda)} U_2 + \left( \frac{\omega \rho c}{\lambda} \right) \left( \frac{j}{\lambda} \right) T^{(RM)} T^{(T\lambda)} U_2 \]
\[ + \left( \frac{\omega \rho c}{\lambda} \right) \left( \frac{j}{\lambda} \right)^2 T^{(2TM)} T^{(R\lambda)} T^{(T\lambda)} U_2 \]
\[ + \left( \frac{\omega \rho c}{\lambda} \right) \left( \frac{j}{\lambda} \right)^3 T^{(RM)} T^{(2TR)} T^{(R\lambda)} T^{(T\lambda)} U_2 \]
\[ + \left( \frac{\omega \rho c}{\lambda} \right) \left( \frac{j}{\lambda} \right)^4 T^{(2TM)} T^{(R\lambda)} T^{(2TR)} T^{(R\lambda)} T^{(T\lambda)} U_2 + \cdots, \tag{12} \]

where \( T^{(T\lambda)} \) is the transfer matrix from transducer 2 to the reflector and \( U_2 \) is the displacement amplitude distribution in transducer 2.

After determining the sound pressure generated by both transducers, the pressure fields \( P_1 \) and \( P_2 \) are added and the potential for acoustic radiation force is determined. In the simulations, the amplitudes of both transducers were kept constant, and the phase of transducer 1 was changed from \(-180^\circ\) to \(+180^\circ\), while keeping the phase of transducer 2 constant. The numerical acoustic radiation potential determined for different phases is shown in Figs. 12(b), 12(d), 12(f), and 12(h).

To verify the matrix model, the positions of minimum acoustic radiation potential, indicated by “+” in Fig. 12, are compared with the levitation positions of a small styrofoam sphere in a noncontact manipulation system. The noncontact manipulation system consists of two 37.9-kHz circular Langevin transducers of 20-mm diameter and a plane reflector. The transducers’ signals are generated by two synchronized 33250A function generators (Agilent Technologies Inc., Santa Clara, CA) and amplified by two 800A3A power amplifiers (Amplifier Research Corp., Souderton, PA). The position of the styrofoam sphere for different excitation phases is captured by a charge-coupled device (CCD) camera. The comparison between the equilibrium position of the sphere and the numerical potential for acoustic radiation force is presented in Fig. 12. Although there are many points of minimum acoustic potential, the bottom levitation position was chosen for levitation. This levitation point is located at a distance of 2.5 mm from the reflector and it was experimentally and numerically verified that this distance is not altered when the phase difference between the two transducers is changed. The experimental horizontal position was determined by changing the phase difference between the two transducers from \(-180^\circ\) to \(180^\circ\) and taking photographs at every \(10^\circ\). The comparison between the experimental horizontal position and the numerically obtained position is shown in Fig. 13. The numerical horizontal position was obtained by numerically determining the position of minimum acoustic radiation potential. As shown in Fig. 13, the position of minimum acoustic potential is not linear with the phase difference between the transducers. Fig. 13 also shows that the noncontact manipulation system allows control of the sphere’s horizontal position from \(-6\) mm to \(6\) mm by changing the phase difference from \(-180^\circ\) to \(180^\circ\).

V. CONCLUSIONS

A new numerical method was presented to determine the potential for acoustic radiation force that acts on a small sphere in an acoustic levitator. The acoustic radiation potential obtained with the matrix method was compared with that obtained by the finite element method, showing good agreement between the two methods. After validating the numerical method, it was applied to the modeling of a noncontact manipulation system. The comparison between the experimental and numerical results shows that the matrix method can be applied to the design of acoustic manipulation systems and it is especially useful in the modeling of acoustic levitators that do not have axisymmetric geometry, because it requires much less computation effort than that required in three-dimensional finite element simulations.
REFERENCES


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