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Effect of physical properties on the oscillation of an acoustically levitated droplet

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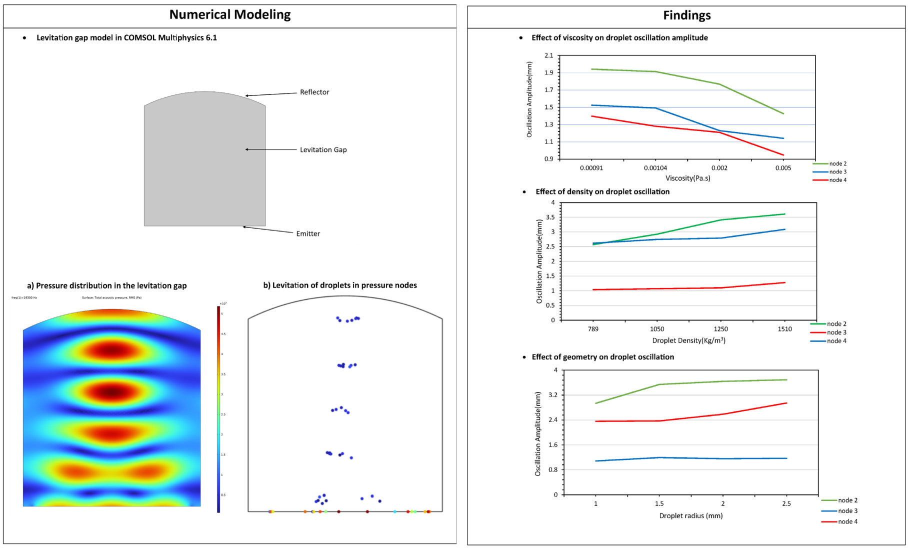
HIGHLIGHTS

- Simulate the ultrasonic levitation process of droplets using the COMSOL Multiphysics software.
- Investigate how the physical properties of droplets, namely viscosity, density, and droplet radius, affect their fluctuation amplitudes.
- Increased viscosity results in greater resistance to deformation for the droplet, thereby maintaining its stability during levitation and reducing oscillation amplitude.
- A higher droplet density leads to increased droplet weight, amplifying the droplet's oscillation amplitude.
- Increasing the radius of the droplet improves the force applied to the droplet with the help of a larger cross-sectional area.

GRAPHICAL ABSTRACT



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ABSTRACT

Acoustic levitation is the only method capable of suspending samples with different material properties and geometries, even in the liquid phase. Despite its widespread applications, droplet levitation still has a problem controlling the droplet's position due to initial oscillations before reaching stability. This research investigates the effects of droplet physical properties, such as viscosity, radius, and density, on droplet oscillation amplitude. For this purpose, numerical simulations that apply the effect of the mentioned properties with acceptable accuracy and precision results were conducted using COMSOL Multiphysics 6.1 commercial software. The unique feature of using a simulation is the ability to study the effect of each parameter independently from the rest of the properties, which is not directly possible in experimental tests. The results emphasize the direct influence of viscosity on droplet oscillation amplitude. They also demonstrated that elevated viscosity leads to a decrease in droplet oscillation amplitude. In addition, increasing the density because of the added weight decreases the droplet amplitude. The droplet radius effect is more complicated because it is associated with two opposite effects. Increased droplet radius has the same effect as viscosity because of weight addition. On the other hand, a larger droplet's radius enlarges the cross-section and leads to a weak increase in droplet amplitude.

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1. Introduction

In levitation processes, non-contact force suspends a sample without contact with a secondary surface. Removing contact reduces energy loss and eliminates the effect of surfaces on the chemical or physical properties of the sample. Also, this makes it possible to control heat and mass transfer accurately. Among various suspension methods, including magnetic levitation [1], electric levitation [2], and optical levitation [3], acoustic levitation is considered the only method that can levitate the sample regardless of its geometry or physical properties [4].

The ability to suspend droplets is a unique feature of acoustic levitation, which was presented by Bux and Muller in 1933 when they reported the levitation of an alcohol droplet by standing waves [5]. Acoustic droplet levitation has been used in a wide range of applications such as transporting [6], separation [7], droplet properties measurement [8], solidification [9], liquid sample structure control [10], and in recent years, making vaccines [11]. It is worth noting that the evaporation of a droplet is one of the most-discussed applications of acoustic levitation because heat transfer and mass transfer can be effectively controlled when the droplet is levitated [12-15]. Oscillating the suspended droplet reduces its positioning accuracy, and enhancing levitated object oscillation control remains a subject of ongoing discussion. The geometry of the levitation medium is one of the main factors that influence the droplet oscillation. Xie *et al.* [16] showed that a curved reflector can enhance the acoustic force and cause less sample oscillation. Subsequently, Baer *et al.* reported that using a curve reflector and emitter halved the oscillation of the levitated sample [17].

Zhang *et al.* mentioned that a droplet's initial shape influences its behavior [18]. An abnormal shape causes a bigger oscillation amplitude. Andrade *et al.* mentioned that changing the levitation gap distance affects the stability of the levitated droplet [19]. After the suspension of one droplet and several droplets simultaneously, Hasegawa and Kono studied droplet fluctuation and reported that the amplitude of the droplet fluctuation in the vertical direction increased dramatically when several levitated droplets existed simultaneously [20]. Hasegawa and Murata observed that the movement amplitude of the levitated droplet in the horizontal direction was significantly greater than that in the vertical direction [21]. Moreover, they noted that droplets experienced more stabilized levitation at the third pressure node.

The crystallization of up to three droplets was observed by McElligott *et al.* in 2022 [22]. According to the study, one droplet's crystallization process can influence the behavior of other droplets. During the transformation of a droplet into ice, an ice layer forms around the droplet and then extends to its core. As a result of the presence of air bubbles inside the droplet, its volume expanded approximately 3.5 times after being frozen. Chen *et al.* studied the evaporation dynamics of levitated droplets under acoustic levitation [23]. They reported that a significant decrease in temperature existed due to the enhancement of the droplet evaporation rate. Because the surface tension of a levitated droplet influences its deformation, Argyris *et al.* measured the surface tension of a droplet based on its behavior in an acoustic field based on a machine learning algorithm [24]. Cancino-Jaque *et al.* presented that a large droplet with a diameter of 6.82 mm can be levitated by setting the upper limit of a sound pressure level in an acoustic field [25].

A comprehensive study on how the physical properties of a droplet can impact its oscillation amplitude during levitation is notably lacking in existing literature. In this paper, a numerical approach has been used to investigate the influence of the droplet's physical properties (viscosity, density, and radius) on droplet levitation, especially on the oscillation amplitude. Furthermore, an increase in density and droplet radius is associated with a rise in oscillation amplitude. It is worth mentioning that the impact of density is more pronounced than that of the droplet's radius in the oscillation of droplets.

2. Materials and methods

2.1. Theoretical Modeling

Studying the forces applied to the droplet during suspension is necessary to understand ultrasonic levitation better. Gravity force, drag force, buoyancy force, and acoustic radiation force are the main forces applied to the droplet.

The acoustic radiation force applied to the droplet with a radius much smaller than the wavelength ($r << \lambda$) can be calculated using the Gorkov equation [26].

$$F_{rad} = -\nabla U \tag{1}$$

In Eq. (1), U is the potential of ultrasound waves, calculated by Eq. (2) [17].

$$U = 2\pi r^3 \left[\frac{f_1}{3\rho_0 c_0^2}\left(p_1^{in}\right)^2 - \frac{f_2\rho_0}{2}\left(u_1^{in}.u_1^{in}\right)\right] \tag{2}$$

In Eq. (2), r is the sample radius, and ρ_0 and c_0 are the air density and sound speed in the air, respectively. Also, the two parameters, f_1 and f_2, are dependent on the properties of the levitated sample and air, which can be considered equal to 1 in this situation. In addition, two parameters u_1^{in} and p_1^{in} are the particle velocity and acoustic pressure applied to the particle. These parameters are dependent on the position in the vertical axis of the levitated sample and are obtained by Eqs. (3) and (4) [27].

$$\left(u_1^{in}.u_1^{in}\right) = \frac{1}{2}\left(\frac{p_0}{\rho_0 c_0}\right)^2 sin^2(kz) \tag{3}$$

$$\left(p_1^{in}\right)^2 = \frac{{p_0}^2}{2} cos^2(kz) \tag{4}$$

In the above equations, p_0 is the acoustic pressure amplitude, k is the wavenumber (ω/c_0), and z is the location of the sample. Finally, Eq. (1) can be rewritten as Eq. (5) [27].

$$F_{rad} = \frac{5\pi r^3 k {\rho_0}^2}{6\rho_0 c_0^2} sin^2(2kz)\,\hat{k} \tag{5}$$

Because the droplet movement in the acoustic field can be assumed to be a harmonic motion, the ultrasonic force applied to the sample (Eq. (5)) can also be equal to a spring equation (Eq. (6)) [27].

$$F_{rad} = K\left(z - z_n\right)\hat{k} \tag{6}$$

In Eq. (6), K is the elastic constant, which can be calculated based on Eq. (7) [27].

$$k = \frac{5\pi r^3 k^2 {\rho_0}^2}{3\rho_0 c_0^2} \tag{7}$$

2.2. Numerical Modeling

Based on finite elements, a numerical model that uses COMSOL Multiphysics software was developed to investigate the effect of the droplet's physical in ultrasonic levitation conditions. As mentioned in section 2.1, the COMSOL Multiphysics 6.1 software simulation procedure needs to create acoustic radiation force, gravity, and drag forces to achieve a simulation with accurate results. Two methods existed in the procedure for this purpose.

In the first, only the levitation gap containing the top surface of the transducer and the reflector exists in the simulation. In the second, the simulation model includes the entire transducer and the reflector. Both simulation techniques were executed in this paper, and the results were validated with the experimental results on the oscillation range of the levitated droplet in the three nodes reported by Hasegawa and Kono [20]. Initial values of the simulation were considered according to the characteristics of the levitation setup [20] (Table 1).

2.2.1. Simulation levitation gap

In the first method, the levitation gap consists of two up-and-down adjacent walls in the simulation. The upper wall represents the reflector, and the lower wall represents the surface of the emitter. Fig. 1 shows the schematic geometry used in this method. In this method, after drawing the geometry based on the dimensions mentioned in Table 1, the bottom wall was selected as the wave generator, which forms waves by defining the wall motion. After that, the upper wall (reflector) was defined as the sound-hard boundary, which causes the waves to return inside the gap. As a result, a standing wave can formed be in the gap.

Table 1. Numerical model parameters.

Parameter	Description	Value
f	Frequency	19.3 [kHz]
c	Speed of sound	343 [m.s^{-1}]
λ (c/f)	Wavelength	17.77 [mm]
H	Gap levitation	$(5/2)\lambda$ = 44.4 [mm]
T_r	Transducer radius	36 [mm]
d_r	Droplet radius	1.5 [mm]
d_p	Droplet density	997 [kg.m^{-3}]
d_v	Droplet viscosity	0.0091[Pa.s]

The acoustic pressure contour created by this method can be seen in Fig. 2(a). In the last step, with the help of particle tracing physics, the behavior of the released droplet at node points can be evaluated (Fig. 2(b)).

2.2.2. Levitation setup simulation

Using this method, the geometrical model should contain the ultrasonic transducer and the reflector. The geometrical model is shown in Fig. 3(a). Using the electrostatic physics module and solid mechanics physics, the process of applying voltage to piezoelectric materials and their displacement was completely simulated. Then, after coupling the solid mechanical physics and the acoustic pressure physics, the

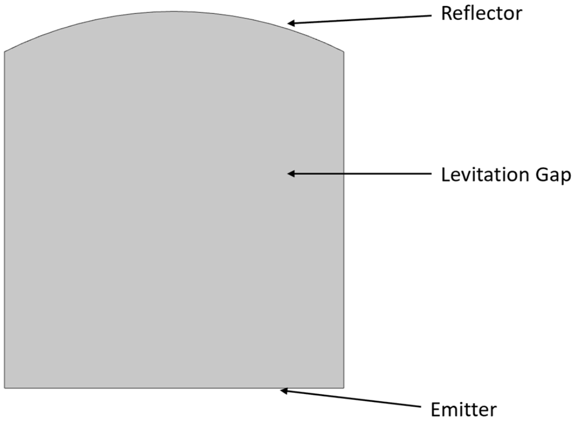

Fig. 1. Levitation space.

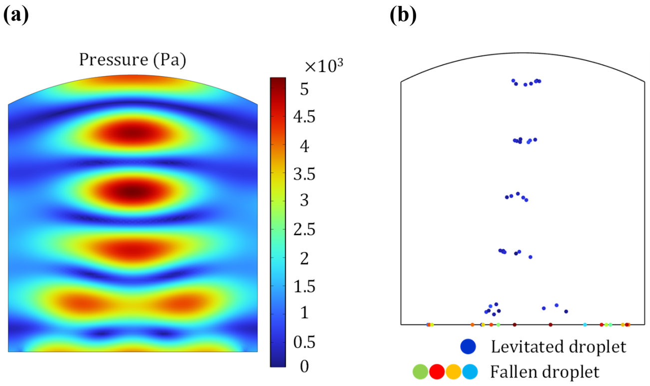

Fig. 2. (a) Pressure distribution in the levitation gap, (b) Levitation of droplets in pressure nodes.

generated waves were emitted first in the transducer and then in the levitation gap, which allows the pressure distribution of ultrasonic waves to be obtained. As explained in section 2.2.1, the particle tracking physics module can be used to study droplet oscillation.

2.3. Validation

Before comparing the two mentioned simulation methods outputs, the results should be as close to the experimental results as possible by optimizing the solution parameters. Parameters such as the mesh size, the allowed error, and the step of solution for the region should be the same in both simulations.

First, the mesh size for the levitation gap was determined by trial and error until the results were independent of the mesh size, resulting in a maximum and minimum mesh size of (λ/10) and (λ/16), respectively. Secondly, the relative tolerance size was determined to be 10-9; hence, the results are independent of this parameter. The size of the time step is another important parameter in achieving the desired results. This parameter should be small enough to record the droplet movement accurately. The maximum value for this factor was set to 0.005.

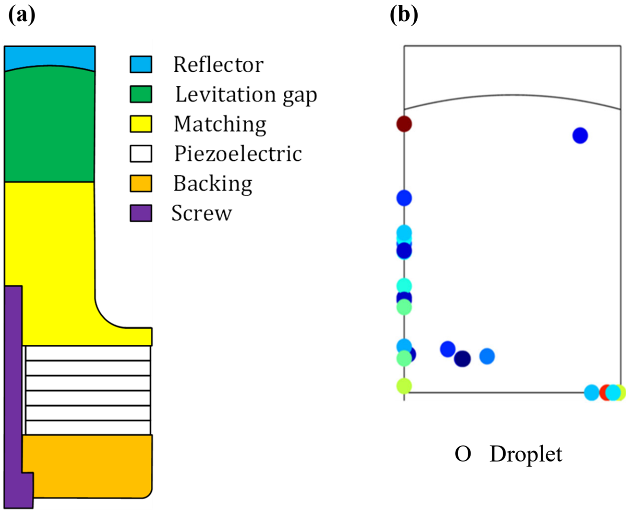

Fig. 3. (a) The Simulation model of the levitation setup, (b) Suspension of droplets in the levitation gap.

In this step, the simulation results should be compared with the experimental results in [20]. According to what was recorded in the experiment, the average sound pressure in the nodes was about 5 kPa. Therefore, the initial and boundary conditions in both simulations should be set so that the pressure of the suspension gap reaches 5 kPa. A comparison of the droplet's oscillation amplitude in the experimental tests [20] and the simulations is presented in Table 2.

Referencing Hasegawa and Kono's [20] findings about the behavior of the droplets in nodes, the oscillation of the droplets in nodes 2, 3, and 4 have been used in this study (due to the negative effect of wave interference in the first and fifth nodes). As summarized in Table 2, the amplitude of the levitated droplets in the experimental test is 1.2 mm in nodes 2 and 3 and 1.1 mm in the fourth node. In the levitation gap simulation, the fluctuation range of the droplet is 1.4 mm in the first node and 1.3 mm in the following two nodes. In other words, the error rate in this method is less than 15%. However, the suspended droplets in the levitation setup simulation recorded an oscillation range of 2 mm in the first node and 2.1 mm and 1.8 mm in the two following nodes, recording a minimum error rate of 38% to the experimental results.

Examining these results, it can be concluded that the levitation gap simulation can be used to investigate the effects of physical properties on droplet behavior. Also, particle tracking physics allows the effects of each droplet's physical property to be independently studied.

3. Results and discussion

3.1. Effect of viscosity on droplet oscillation

Particle tracking physics is used in this study to simultaneously track particles at all nodes. As a result of using this type of study, the effect of changes in the droplet's physical properties, such as viscosity, can be observed accurately when other physical parameters are kept constant. Furthermore, the applied changes must not alter the pressure distribution of the wave, which increases the study's accuracy.

In this section, the radius and density of the droplet were selected according to Table 1, and the effect of the droplet's viscosity on the fluctuation range was investigated. According to Fig. 2, the amplitudes of the droplets in the vertical direction with four viscosities were recorded in the second, third, and fourth nodes during certain intervals of time (5 s). Because the fluctuations of a droplet gradually decrease over time and

Table 2. Oscillation ranges in experimental tests and simulations.

Node	**Oscillation amplitude in experimental test (mm)**	**Results of levitation gap (simulation)**		**Results of levitation setup (simulation)**	
		Droplet oscillation amplitude (mm)	**Percentage error (%)**	**Droplet oscillation amplitude (mm)**	**Percentage error (%)**
Second node	1.2	1.4	14	2	40
Third node	1.2	1.4	7.7	2.1	42
Fourth node	1.2	1.3	15	1.8	38

reach a stable position, the droplet's maximum oscillation range should be considered in the first moments of its release. A larger oscillation amplitude is viewed as a negative factor since it reduces the accuracy of the initial positioning and increases the time required for the droplet to stabilize.

Fig. 4 shows that the increase in viscosity in all three nodes significantly reduced the oscillation amplitude of the droplets. It is worth noting that, during the levitation of a droplet, different forces containing acoustic radiation, gravity, and drag are applied to the droplet in opposite directions, which can result in a deformation in the droplet. The viscosity has a direct effect on the amount and manner of this deformation. In other words, an increase in the viscosity improves the resistance of the droplet against changing its shape. This deformation changes the pressure distribution on the droplet surface, which can upset the balance of the forces acting on the droplet and cause more fluctuation.

It is interesting to note that viscosity has the highest effect on the droplet oscillation amplitude in the fourth node, but the changes in trends in the other two nodes are close to each other.

3.2. *Effect of density on droplet oscillation*

The droplet's density is one of its physical properties that can affect its oscillation during levitation. With a change in density, it is possible to investigate how weight changes affect the oscillation amplitude of a suspended droplet without affecting any other properties.

Based on section 2.1, the droplet's movement model can be compared to a vibrating system. In this system, the stiffness coefficient is calculated based on the physical properties of the ground fluid (air) and the properties of the created wave. Also, the radius of the levitated droplet directly affects the system's vibrating behavior. Hence, keeping the mentioned parameters constant and increasing the density of the droplet causes a growth trend in the fluctuation range (Fig. 5). According to the figure, the oscillation amplitude of the suspended droplets increases by 28.8%, 18.6%, and 15.5 % in nodes 2, 3, and 4 when the droplet density is approximately doubled. Accordingly, increasing the density of the droplet while keeping its diameter constant means expanding the mass of the levitated droplet, keeping the other vibrating system characteristics, such as the equivalent stiffness coefficient, constant. As a result, putting droplets with a higher density in the system is like applying more gravity force to the system, which leads to more instability.

3.3. *Effect of geometry on droplet oscillation*

Changing the radius of a droplet means changing its cross-section and weight simultaneously. Therefore, this

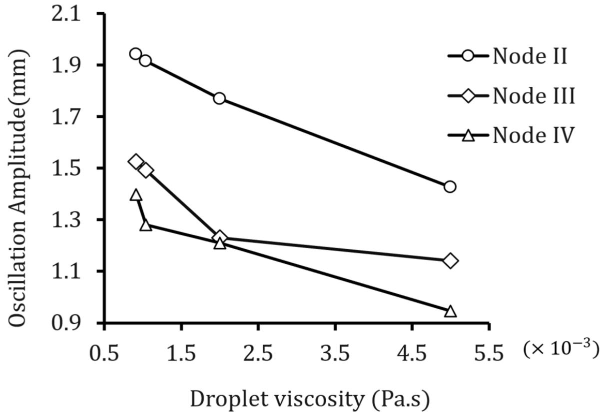

Fig. 4. Effect of droplet's viscosity on oscillation at 3 nodes.

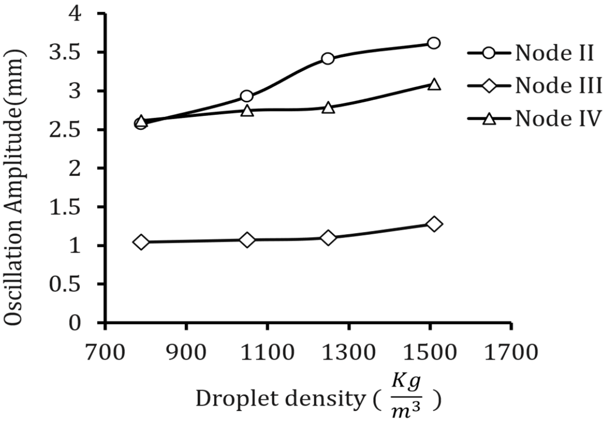

Fig. 5. Effect of droplet density on oscillation at 3 nodes.

investigation can determine the effect of two parameters on the fluctuation of the droplets.

According to Fig. 6, expanding the radius of the droplets caused an increase in the range of droplet oscillation in all three nodes. Predictably, enlarging the droplet's radius causes a significant growth in the oscillation amplitude because of the increase in the droplet weight. Despite this, more acoustic force is applied to the droplet due to the increase in the droplet's cross-section area, which leads to less growth compared to Fig. 5's oscillation amplitude. In other words, the increase in density and diameter increases the gravitational force entering the droplet (due to the increment in mass), but as the diameter increases, some of this force is compensated by applying more acoustic force. The second node showed the most enhancement in the oscillation range as a result of changing the radius.

Besides the fluctuations of the levitated droplet, the levitation time length is another main working factor because more levitating time is preferable in most applications. The levitation time can be increased by reducing the time during the stabilization region so that the change in the droplet's shape and its atomization occurs later. According to the physical properties presented in this paper, levitated droplet behavior can be used to predict the time needed to reach droplet stability.

4. Conclusion

While the applications of acoustic levitation continue to grow, especially as the primary method for suspending liquids across various fields, such as chemistry and transportation, a notable drawback of this process is the limited study of droplet movement before achieving stability at the nodes. This study used COMSOL Multiphysics software to simulate the ultrasonic levitation process to investigate how the physical properties of droplets, namely viscosity, density, and droplet radius, affect fluctuation amplitudes. The key findings of this paper are summarized as follows:

- Increased viscosity results in higher resistance to deformation for the droplet, thereby maintaining its stability during levitation and reducing oscillation amplitude.
- Increasing droplet density and weight increases the droplet's oscillation amplitude.
- Increasing the radius of the droplet enhances the force applied to the droplet due to a larger cross-sectional area. This force reduces the effect of increasing the weight because of the expansion of the radius, but the growth of the movement amplitude still exists.

These findings provide valuable insights into the dynamics of droplet oscillation during ultrasonic levitation, offering potential applications and optimizations in various fields.

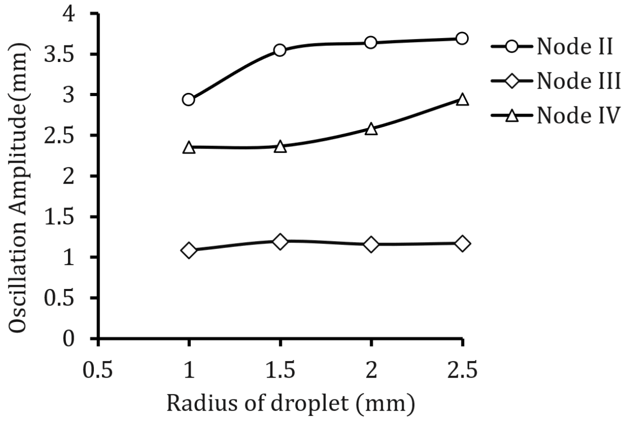

Fig. 6. Effect of droplet radius on oscillation at 3 nodes.

Nomenclature

r	Sample radius
ρ_0	Air density
c_0	Sound speed in air
u_1^{in}	Particle velocity
p_1^{in}	Acoustic pressure
p_0	Acoustic pressure amplitude
k	Wavenumber
z	Location of the sample
K	Elastic constant
f	Frequency
c	Speed of sound
λ	Wavelength
H	Gap levitation
T_r	Transducer radius
d_r	Droplet radius
d_ρ	Droplet density
d_v	Droplet viscosity

Disclosure statement

No potential conflict of interest was reported by the authors.

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Additional information

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