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Acoustic levitation of a large solid sphere

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Abstract: We demonstrate that acoustic levitation can levitate spherical objects much larger than the acoustic wavelength in air. The acoustic levitation of an expanded polystyrene sphere of 50 mm in diameter, corresponding to 3.6 times the wavelength, is achieved by using three 25 kHz ultrasonic transducers arranged in a tripod fashion. In this configuration, a standing wave is created between the transducers and the sphere. The axial acoustic radiation force generated by each transducer on the sphere was modeled numerically as a function of the distance between the sphere and the transducer. The theoretical acoustic radiation force was verified experimentally in a setup consisting of an electronic scale and an ultrasonic transducer mounted on a motorized linear stage. The comparison between the numerical and experimental acoustic radiation forces presents a good agreement.

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Small particles and liquid droplets experience a net force when they are placed in an acoustic field. This force is called acoustic radiation force[1-3], and if it is strong enough, it can be used to levitate[4,5] and to manipulate[6,7] small objects in air. There are different techniques to acoustically levitate objects in air. The most common consists of producing a standing wave field between an ultrasonic transducer and a reflector, allowing small particles to be levitated at the acoustic pressure nodes of the standing wave. This technique, which is illustrated in Fig. 1(a), can be divided in two configurations: resonant[8-10] and non-resonant[11,12]. In resonant levitation devices, the distance between the transducer and the reflector should be approximately equal to a multiple of a half wavelength. In this configuration, it is possible to obtain high intensity acoustic fields, and therefore high mechanical force, allowing the levitation of high density materials such as mercury or iridium[13]. In a non-resonant configuration, the distance between the reflector and the transducer can be selected at will, without requiring the separation distance to be set to a multiple of a half wavelength. In this configuration, small light particles can be manipulated by maintaining the transducer at a fixed position and moving the reflector in relation to the transducer[11]. Another technique to acoustically levitate objects is the near-field acoustic levitation (also called squeeze-film levitation)[14]. As illustrated in Fig. 2(b), this technique allows levitating heavy planar objects at a distance of tens of micrometers from the transducer radiating surface. Variations of this technique are capable of levitating spheres[15] and cylindrical shaped objects[16].

In the last few years, a new acoustic trapping technique, called single-beam trapping, was demonstrated in liquid media[17-19]. This technique, illustrated in Fig. 1(c), uses a focused transducer to trap particles around the focus point. Recently, this technique was extended to allow the levitation and manipulation of small particles in air[20]. In a demonstration of their setup, Marzo and coauthors[20] used a single-sided array of 40 kHz transducers to levitate and to manipulate small expanded polystyrene particles in three dimensions.

So far, levitation methods based on standing waves and in the single-beam acoustic trapping mode are used almost exclusively to levitate particles smaller than a half wavelength. In contrast, near-field acoustic levitation is capable of levitating larger objects, but the maximum levitating height is limited to few hundreds of micrometers. The possibility of using acoustic standing waves to levitate objects larger than the wavelength has been demonstrated only for very specific cases, such as wire-liked[6] and planar[21] objects. In one of these demonstrations, Zhao and Wallaschek[21] used a 19 kHz ultrasonic transducer to levitate a compact disc at a distance corresponding to a half wavelength from the transducer radiating surface. However, their system has the disadvantage of only being capable of producing acoustic forces in the vertical direction and a central pin was necessary to provide lateral stability to the levitated disc.

In this letter, we demonstrate the acoustic levitation of a large spherical object in air. This is achieved by using three 25 kHz ultrasonic transducers to produce an acoustic standing wave between the transducers and the sphere. This levitation concept is illustrated in Fig. 1(d) and it allows complete 3D stability of the levitated object. In order to understand the levitation behavior, the acoustic radiation force produced by each transducer on the sphere is determined numerically as a function of the distance between the sphere and the transducers. The acoustic radiation force on the sphere is also measured experimentally by using an electronic scale.

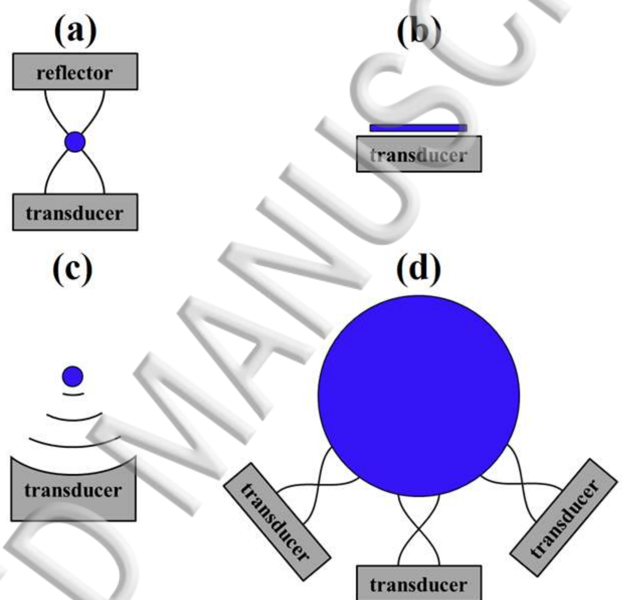

FIG. 1. Types of acoustic levitation: (a) Standing wave; (b) Near-field; (c) Single-beam trapping; (d) Proposed levitation concept.

The acoustic levitation of a sphere (50 mm in diameter, weighting 1.46 grams) larger than the wavelength was achieved by the combination of three 25 kHz bolt-clamped Langevin type transducers with a circular radiating face of 20 mm in diameter. The resonance frequency of each transducer varies up to 2% due to fabrication tolerance and temperature variation. For this reason, the transducers were excited independently by using two function generators (one single-channel and one dual-channel) connected to three power amplifiers. As illustrated in Fig. 2, the transducers were arranged in a tripod fashion, with each transducer being adjusted such that its main axis coincides with the sphere center. It is also important to adjust the distance between the transducer and the sphere surface to approximately a half wavelength. The tripod configuration was chosen due to the levitation stability that is achieved in both vertical and horizontal directions. In the configuration of Fig. 2, two transducers were inclined by an angle of approximately 50° in respect to the horizontal plane and the third one was inclined by angle of 60°. In the configuration of Fig. 2, most of the vertical force on the sphere is exerted by the 60° angled transducer and this different angle was chosen for the purpose of visualization. Similarly to a tripod, the transducer angles can be chosen almost arbitrarily, with higher angles (in respect to the horizontal plane) providing higher vertical acoustic forces and lower angles providing better horizontal stability. The configuration of Fig. 2 can also be modified to include more transducers. One possibility is to use one bottom transducer to generate vertical force and three horizontal transducers separated by 120° to provide horizontal stability.

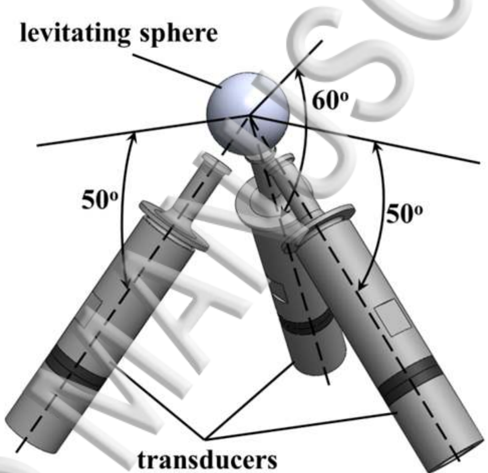

FIG. 2. Schematic of the acoustic levitation system.

The levitation capability of the proposed system was confirmed by levitating an expanded polystyrene sphere with a mass of 1.46 g and diameter of 50 mm. This sphere size is approximately 3.6 times larger than the wavelength ($\lambda \approx 13.8$ mm). In order to produce enough acoustic radiation force on the sphere, the transducers were operated with a displacement amplitude in the range 15-20 μm. A picture showing the acoustic levitation of the large expanded polystyrene sphere is presented in Fig. 3 and a demonstration video is available online (Multimedia view 1). During the levitation experiments, the distances between the sphere surface and the transducers were slightly higher than a half wavelength ($\lambda/2 \approx 6.9$ mm).

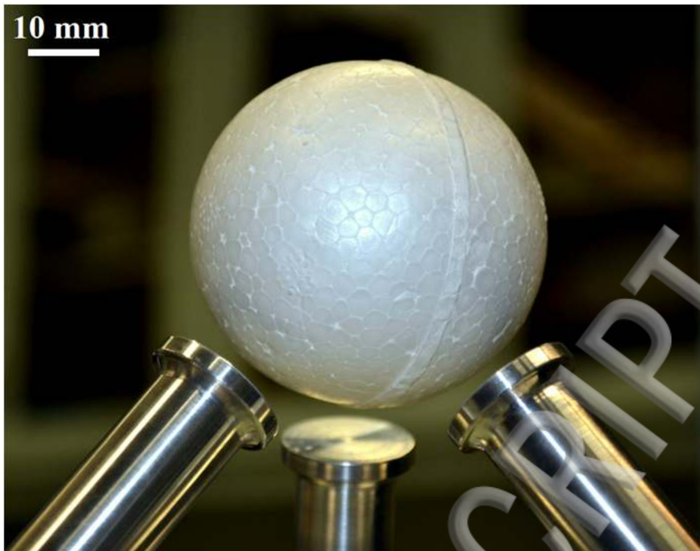

FIG. 3. Acoustic levitation of an expanded polystyrene sphere of 50 mm diameter by using three circular ultrasonic transducers of 25 kHz. A demonstration video with the acoustic levitation of a large sphere is available online (Multimedia view 1).

The axial acoustic radiation force exerted on the large sphere by the acoustic wave generated by one transducer is calculated by using the Finite Element Method. To obtain the acoustic radiation force, a 2D axisymmetric linear acoustic model is implemented in the software COMSOL Multiphysics. The axisymmetric model, illustrated in Fig. 4(a), allows to compute the first-order acoustic pressure p_1 and first-order velocity $\mathbf{u_1}$ in the air region around the sphere. In this model, H is the distance between the transducer and the sphere surface and it is considered that the transducer surface vibrates harmonically with displacement amplitude of 15 μm at a frequency of 25230 Hz. Perfectly matched layers (PML) are employed to avoid wave reflections at the extremities of the air domain and an acoustic hard boundary condition is applied on the sphere surface. In accordance with the experimental conditions at 25 °C, air density ρ_0 and air velocity c_0 were set to 1.18 kg/m^3 and 346 m/s, respectively. From the first-order fields p_1 and $\mathbf{u_1}$, the acoustic radiation force $\mathbf{F}_{\text{rad}}$ on the sphere can be modeled as[3]:

$$\mathbf{F}_{\text{rad}} = -\int_{S_0} \left\{ \left[\frac{\langle p_1{}^2 \rangle}{2\rho_0 c_0^2} - \frac{\rho_0 \langle \mathbf{u_1} \cdot \mathbf{u_1} \rangle}{2} \right] \mathbf{n} + \rho_0 \langle (\mathbf{n} \cdot \mathbf{u_1}) \mathbf{u_1} \rangle \right\} dS \, , \tag{1}$$

where $\langle \; \rangle$ denotes time average, the surface normal vector $\mathbf{n}$ points outward from the enclosed volume and the integral is evaluated over the closed surface S_0 of Fig. 4(a). As described by Bruus[3], the integral of Eq. (1) can be evaluated in any closed surface encompassing the sphere.

By using the numerical model illustrated in Fig. 4(a), the first-order acoustic pressure distribution and the axial acoustic radiation force on a rigid sphere of 50 mm diameter were obtained for H varying from 2 mm to 30 mm. Figure 5 shows the acoustic axial radiation force on the sphere when changing the distance between the sphere and the transducer. It can be seen that the first maximum radiation force is obtained for H = 7.2 mm, which is slightly higher than a half wavelength ($\lambda/2 \approx 6.9$ mm). This small difference can be attributed to the fact that the standing wave in the air gap between the sphere and the transducer is not exactly a plane wave[22]. The simulated acoustic pressure amplitude for H = 7.2 mm is presented in Fig. 4(b), which shows that a standing wave field is created in the air gap between the transducer and the sphere. A video showing the simulated acoustic wave generated by the transducer is available online (Multimedia view 2). The numerical model was also applied to estimate the maximum sphere size that could be levitated with the present setup. Considering the setup of Fig. 2 operating at 25230 Hz with displacement amplitude of 15 µm, the maximum sphere diameter that could be levitated corresponds to approximately 65 mm (for further details, see supplementary material[28]).

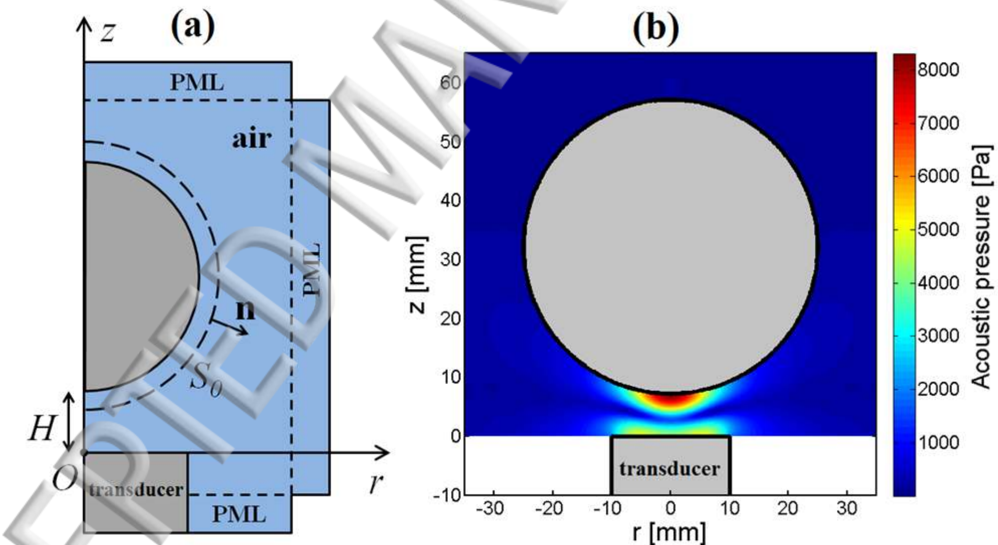

FIG. 4. (a) Description of the finite element model; (b) First-order acoustic pressure obtained numerically for H = 7.2 mm, transducer displacement amplitude of 15 µm, and frequency of 25230 Hz. A video showing the simulated wave emitted by the transducer is available online (Multimedia view 2).

In order to verify the theoretical model, the actual force acting on the sphere was measured experimentally and compared to the numerical results. To measure the acoustic radiation force, the expanded polystyrene sphere was placed on an electronic scale[23]. One of the transducers used in the levitation experiments was positioned above the sphere, with its radiating face pointing towards the sphere. The transducer was mounted on a motorized linear translation stage and the acoustic radiation force on the sphere was measured by moving the transducer from $H = 0.1$ mm to 30 mm in steps of 0.1 mm. In this experiment, the transducer operated at a frequency of 25230 Hz with displacement amplitude of 15 μm. The comparison between the simulated and the experimental acoustic radiation force on the sphere is presented in Fig. 5 and a good agreement between both forces can be observed. The difference between experimental and numerical peak values is attributed to experimental uncertainties and to some simplifying assumptions in the numerical model, such as considering a rigid sphere and assuming uniform displacement along the transducer face. Additionally, the numerical model is linear and cannot predict nonlinear effects such as harmonic generation[23] and acoustic streaming[24].

In order to have a stable acoustic levitation, there should be a restoring force on the sphere. This is only possible if the sphere is located in the descending parts of the curve in Fig. 5. In this case, if a small perturbation moves the sphere towards one transducer, the acoustic radiation force increases, moving the sphere back to its equilibrium position. In contrast, if a small perturbation moves the sphere upwards, the acoustic radiation force decreases and the gravity force brings the sphere back to its resting position. For the first resonance mode, a stable levitation occurs when the sphere is positioned on the descending part of the peak, i.e. for H varying from 7.2 mm to approximately 10 mm. In principle, the other peaks could also be used for levitating the sphere, but in our experiment, the acoustic radiation force provided by the other peaks was not strong enough to suspend the sphere.

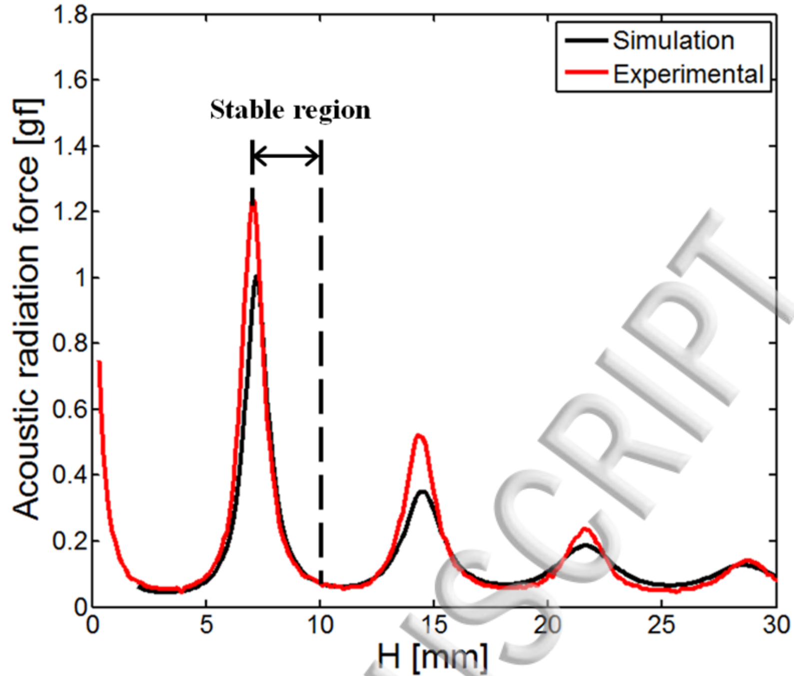

FIG. 5. Comparison between simulated and experimental acoustic radiation force on the sphere for a transducer displacement amplitude of 15 µm.

Although the levitation of a large sphere was demonstrated, the proposed concept of Fig. 1(d) is not restricted to spheres and it could be extended to objects of different shapes and sizes. The proposed levitation concept could also be applied to material handling and processing in space[25,26]. One particular application is in the trapping of large liquid samples in microgravity, which could be achieved by placing different transducers around the liquid sample. In contrast with Earth's environment where the surface tension limits the maximum drop size that can be levitated, the acoustic forces in a microgravity environment can be considerably reduced such that surface tension dominates, thus allowing the handling of large liquid samples. Another possible application is in the contactless handling of high temperature materials[27]. For further information, please refer to the supplementary material[28].

In summary, we demonstrated that acoustic levitation is not restricted to particles smaller than a half wavelength. In our experiments, a sphere of a diameter 3.6 times larger than the acoustic wavelength was suspended by a standing wave field in air. In contrast to traditional standing wave levitators where small particles are trapped at the pressure nodes, the levitation of a large spherical object occurs because a standing wave is produced between the transducers and the object itself. By employing three ultrasonic transducers in a tripod fashion, complete 3D stability was achieved, i.e both laterally and axially, allowing the levitation of a large sphere in air, without any contact with solid surfaces. Although the acoustic levitation was demonstrated with a sphere of 3.6 times the wavelength, we believe that the technique can be easily extended to levitate objects of different shapes and sizes.

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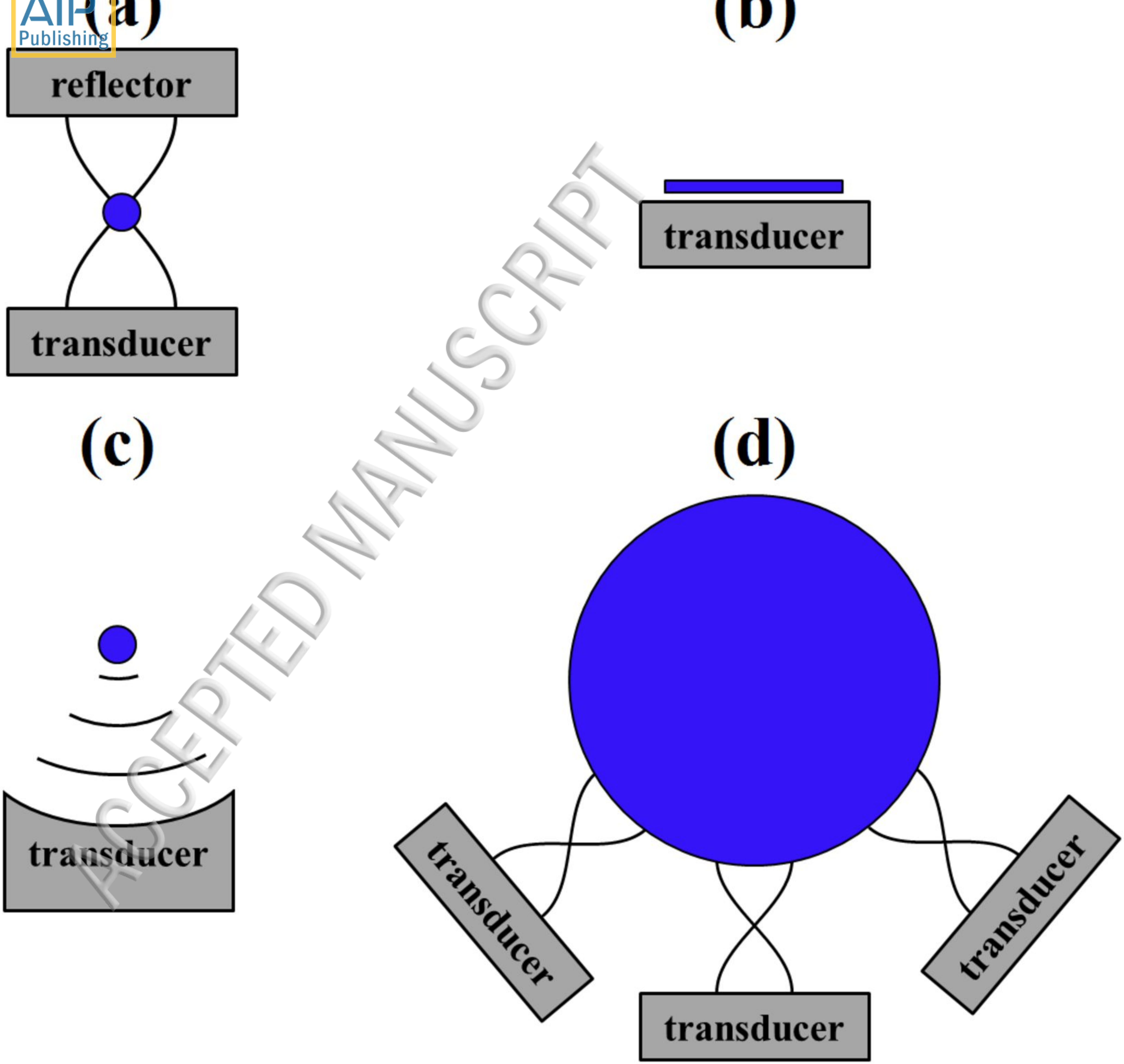
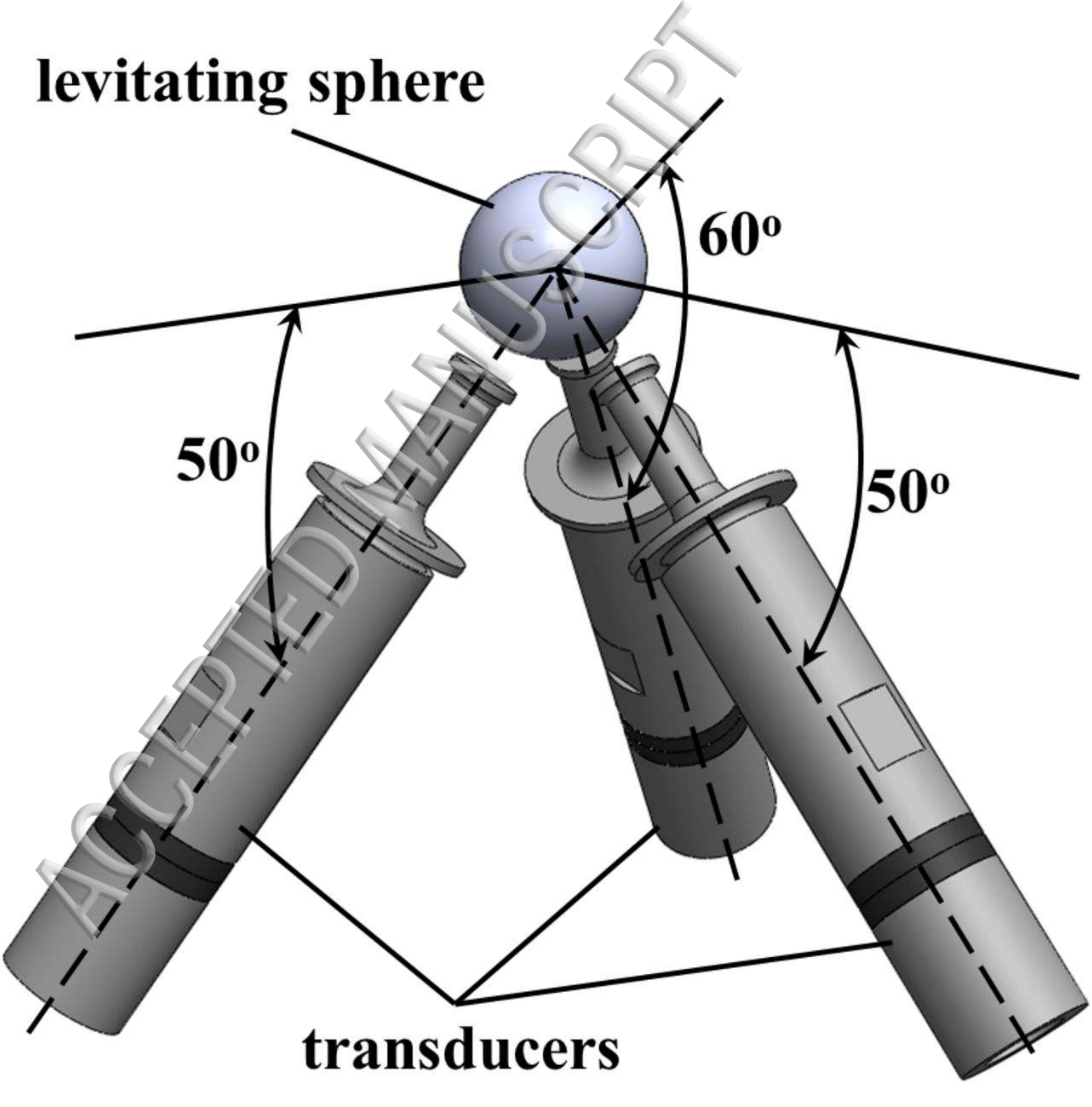
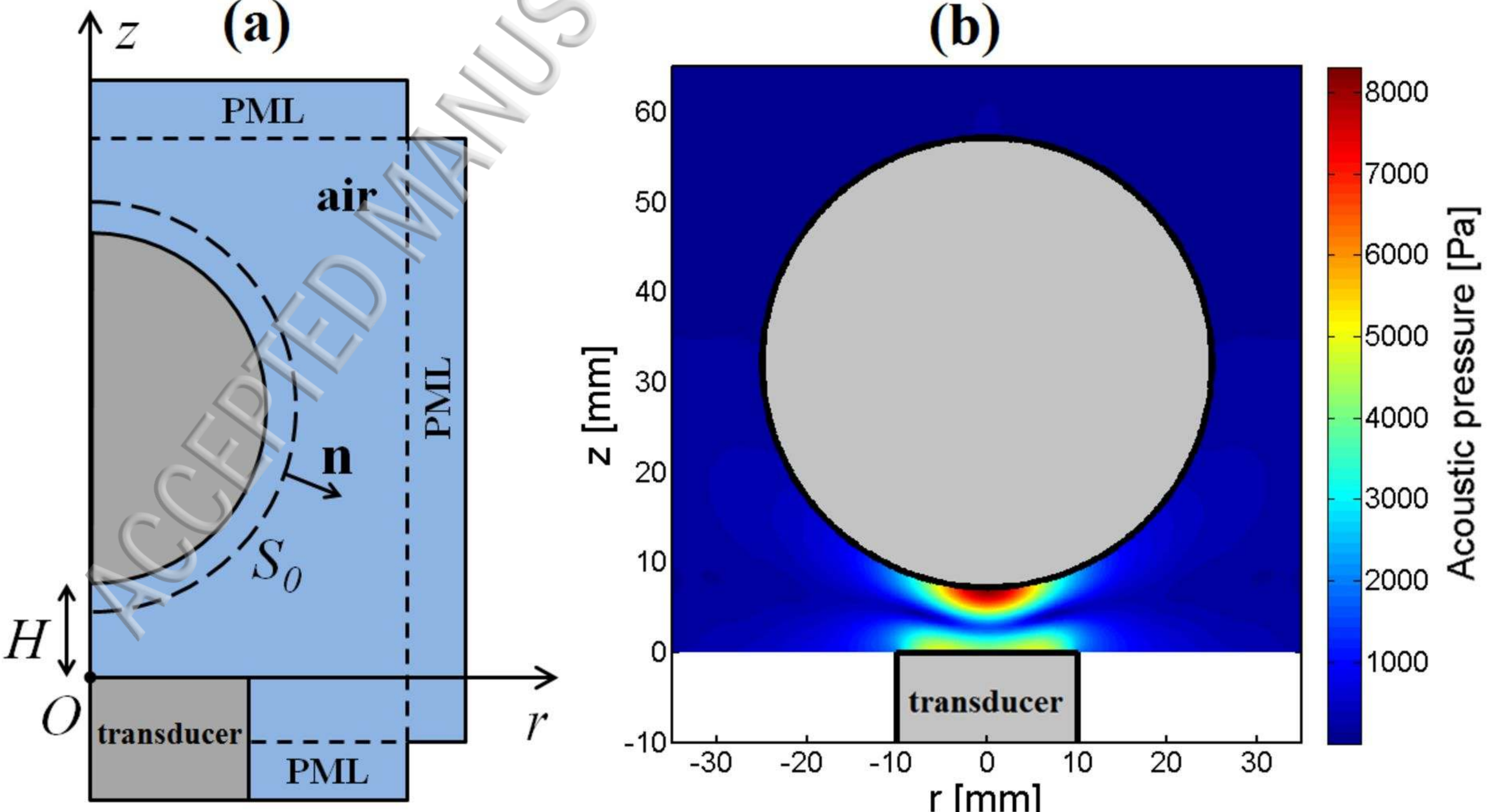
[28]See supplementary material for details about the maximum sphere size and suggested extension for the levitation concept.

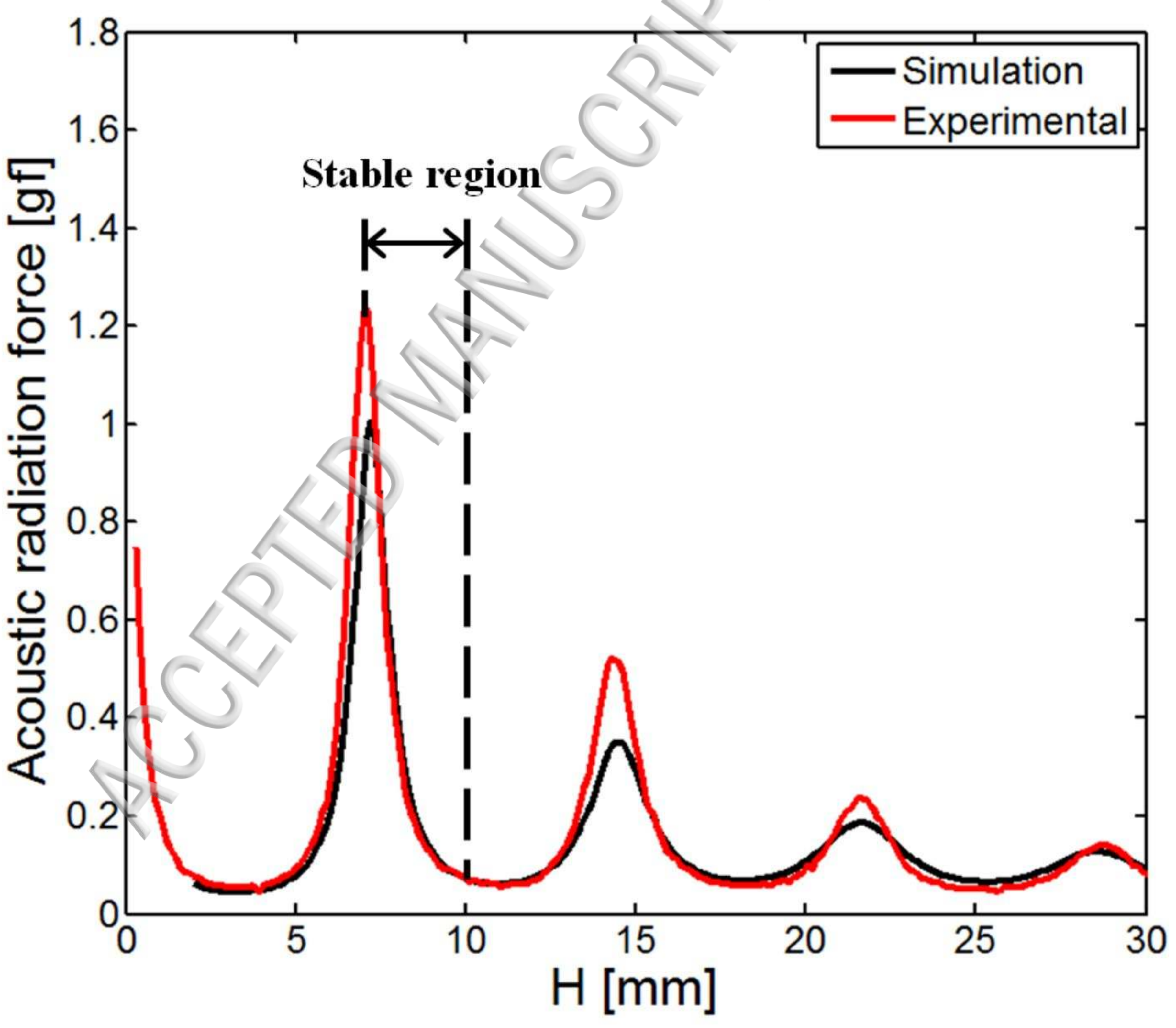


(a)
reflector
transducer
(b)
transducer
(c)
transducer
(d)
transducer
transducer
transducer


levitating sphere
60º
50º
50º
transducers


10 mm


(a)
z
PML
air
PML
n
S_0
H
O
transducer
PML
r
(b)
60
50
40
30
20
10
0
-10
z [mm]
-30
-20
-10
0
10
20
30
r [mm]
transducer
8000
7000
6000
5000
4000
3000
2000
1000
Acoustic pressure [Pa]



Simulation
Experimental
Stable region
Acoustic radiation force [gf]
H [mm]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
5
10
15
20
25
30