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ABSTRACT

The acoustic levitation of liquid drops has been a key phenomenon for more than 40 years, driven partly by the ability to mimic a microgravity environment. It has seen more than 700 research articles published in this time and has seen a recent resurgence in the past 5 years, thanks to low cost developments. As well as investigating the basic physics of levitated drops, acoustic levitation has been touted for container free delivery of samples to a variety of measurements systems, most notably in various spectroscopy techniques including Raman and Fourier transform infrared in addition to numerous X-ray techniques. For 30 years, the workhorse of the acoustic levitation apparatus was a stack comprising a piezoelectric transducer coupled to a horn shaped radiative element often referred to as the Langevin horn. Decades of effort have been dedicated to such devices, paired with a matching and opposing device or a reflector, but they have a significant dependence on temperature and require precision alignment. The last decade has seen a significant shift away from these in favor of arrays of digitally driven, inexpensive transducers, giving a new dynamic to the topic which we review herein.

INTRODUCTION

Levitation has been used for many years to manipulate materials within air and liquid environments without physical interaction with the container surface. It aims to create a microgravity environment to study the materials which are levitated. There are many forms of levitation including acoustic, magnetic, electrostatic, optical, and aerodynamic. Suspension against gravity using magnetic levitation requires either the sample to be ferromagnetic or the magnetic fields to be among the largest produced on Earth in order to levitate diamagnetic materials which has, for example, been used to levitate a frog.[1] Electrostatic levitation uses an electric field to levitate the sample, requiring a sample which can, and must, be charged in order to achieve suspension against gravity.[2] Optical levitation has only been achieved for very small and lightweight particles as it is achieved by firing a focused laser beam at the sample and utilizing the transfer of momentum from the photons to the sample surface. For this method, the refractive index of the particle must be higher than that of the medium it is suspended within, limiting this technique to a very small number of cases.[3] Finally, aerodynamic levitation is achieved using a high-pressure gas jet to suspend the material under investigation, but this causes significant agitation and may alter the sample in question.[4] In contrast, acoustic levitation is, for a wide range of cases, a superior presentation method as the variety of materials which may be levitated is far greater since there is no requirement for magnetic or chargeable samples. These systems use an emitter and reflector or multiple emitters that produce frequencies above that which can be heard by an average human, to create a series of positions in which the conditions are suitable to entrap particles or sample droplets.

Acoustic levitation was first conceived as a method to allow for microgravity experiments for space applications to be conducted on Earth, by Wang at the NASA Jet Propulsion Laboratory.[5] In this work, three orthogonal standing waves are produced using high power transducers which are capable of suspending liquid samples against gravity and imparting levitation, rotation, and oscillation. The core topics of acoustic levitation have been extensively covered in previous review articles: Work by Brandt[6] has covered the principles of the different types of levitations, whereas Andrade *et al.*[7] completed a comprehensive review of acoustic levitation.

Santesson and Nilsson[8] have also published a review to inform the use of acoustic levitators within chemistry, describing the various processes which can be aided by its use. These reviews have, however, mainly covered the use of traditional acoustic levitation systems primarily utilizing the Langevin horn. Although a key source of ultrasonic radiation, they often require more than 1000 V to power them at powers over 130 W and often cause heating to the sample which is suspended.[9,10] The modern trend toward arrays of cheaper low power off-the-shelf transducers achieves similar suspension forces to some Langevin horns but with negligible heating of the sample and typically a power supply of 12–15 V at powers less than 10 W.[11]

Acoustic levitation has been well demonstrated as a technique for the containerless suspension of samples for remote analysis. It has been used in synchrotron,[12–15] x-ray,[16–18] and Raman spectroscopy[19–21] experiments. A range of additional spectroscopy experiments have also been performed, including Fourier Transform InfraRed (FTIR) spectroscopy,[22–26] X-ray spectroscopy,[27] fluorescence spectroscopy,[28] and mass spectroscopy.[29–31]

The current state of the art for spectroscopic analysis of levitated liquid droplets using a conventional piezoelectric horn levitator is reported by Brotton *et al.*[23,25] In this work, a piezoelectric transducer oscillates at 58 kHz (using $v = f\lambda$ and the speed of sound in air at STP, yielding a wavelength in air of about 5.9 mm). In the earlier of these two papers, the largest diameter of particles that could be levitated was approximately 2.5 mm, whereas the smallest was around 15 μm. In the later paper, the size claimed was up to 3 mm which is at the half wavelength diameter limit. Their measurement system combined Raman, near-IR, UV-vis, and FTIR spectroscopies within the same measurement chamber that also allowed laser heating of the sample droplet. Owing to the small total heat capacity, the levitated particle can be heated to a high temperature and cooled over very short time scales, thus allowing for precise control of the sample temperature. Exemplary state of the art for X-ray diffraction of levitated droplets is reported by Tsujino and Tomizaki[15] at the X06SA beamline at the Swiss Light Source. Their levitation system operated at around 38 kHz (corresponding to a wavelength in air of 9 mm). Rapid spinning of the crystal orientation inside the droplet, which is typical of levitated drops, meant that additional instrumentation for sample oscillation and rotation typically used with standard crystallography was not required. Typically using a 4 μl droplet, consistent with the smallest size droplets reported by Brotton *et al.*, a dataset of 3600 diffraction images per run could be collected in a total duration of around 30 s. These parameters define the range which is needed for phased arrays to compete with the best of the Langevin horn systems for presenting liquid droplets to measurement systems.

This article reviews the acoustic levitation methods which utilize transducer arrays to levitate and manipulate objects within air and their use as a sample suspension or delivery method for measurement systems. It follows the technological development journey from levitating expanded polystyrene particles to levitating droplets through applications.

FUNDAMENTAL PHYSICS OF ACOUSTIC LEVITATION

The reader is directed to comprehensive reviews on the physics of acoustic levitation for thorough treatment of the background physics. However, in the interests of completeness and to ensure that following discussions are fully accessible, the essential analysis of the acoustic force which suspends the samples against gravity is briefly discussed here. Although the physical embodiment of an acoustic levitator may be highly complex, there are relatively few parameters needed to describe the so-called acoustic radiation force which describes the acoustic force exerted on a levitated sample. There are two primary approaches to this analysis which are discussed here. Gor'kov's expression is most often used for evaluation of small sample levitation in focal point systems, estimating the force upon a spherical particle in an arbitrary acoustic field within an ideal fluid. It considers the compressibility of the particle and that it may be set into motion due to the incident wave. In order to apply this expression, it is assumed that the radius of the spherical particle is much smaller than λ, the wavelength of the longitudinal wave which in many applications is on the order of 1–10 mm. It should be noted that for phased arrays which are the primary focus of this review article, the frequency of the transducers (which determines the wavelength) is often based on availability of mass-produced transducers used for ultrasonic range finding or level detection which is typically 38–40 kHz.

To determine the acoustic radiation force, it is first necessary to calculate the time-averaged potential U, as in the following equation:

$$U = 2\pi R^3\left[\left(\overline{p_{in}^2}/3\rho c^2\right)f_1 - \left(\rho\overline{v_{in}^2}/2\right)f_2\right], \tag{1}$$

where R is the radius of the spherical particle and $\overline{p_{in}^2}$ and $\overline{v_{in}^2}$ are the mean-square fluctuations of the pressure and velocity, respectively, at the point of the wave's interaction with the particle.

The factors f_1 and f_2 are described by the following equation:

$$f_1 = 1 - \rho c^2/p_s c_s^2, \quad f_2 = 2(\rho_s - \rho)/(2\rho_s + \rho), \tag{2}$$

where ρ is the density of the fluid, ρ_s is the density of the particle, while c and c_s are the speeds of sound within the fluid and particle, respectively.

The acoustic radiation force acting upon the particle may then be obtained from this result by finding the gradient of the potential.[32]

This approach is, however, not applicable to the levitation of large samples, and an alternative approach is needed to evaluate broad arrays such as used in haptic systems. This analysis requires determination of the acoustic radiation pressure P by assuming a plane wave as can be seen in the following equation:

$$P = \alpha E = \alpha\frac{I}{v} = \alpha\frac{p^2}{\rho v^2}, \tag{3}$$

where the ultrasound energy density is represented by E, I is the sound intensity, the speed of sound in air is given by v, p is the rms ultrasound pressure of ultrasound, and ρ is the air density. Finally, α is a constant between 1 and 2 which scales the resulting pressure to account for the reflectivity of the levitated object with a value of 1 being complete absorption and 2 being complete reflection. Using this relationship, it can be seen that by manipulating the spatial distribution of the ultrasound pressure, the acoustic radiation pressure can be controlled to provide a desired distribution for a given sample.

THE POLYSTYRENE PARTICLE YEARS

Levitation of liquid drops poses a significant challenge owing to the plethora of sample properties which dictate droplet shape. As a consequence, the levitation of expanded polystyrene particles has often heralded the introduction of a novel technique that has later been refined to accommodate liquids. Indeed, levitation was not the aim of much of the work that leads to these developments but a key development step in the production of a new generation of holographic display technologies. In *Noncontact Tactile Display Based on Radiation Pressure of Airborne Ultrasound*,[33] Hoshi *et al.* demonstrated an array of ultrasonic transducers that allowed users to feel virtual objects in air, giving tactile feedback without any mechanical contact. Their prototype consisted of an array of 324, 40 kHz ultrasound transducers where the phase and intensity of each transducer were controlled individually based on the analysis of Eq. (3) to generate an acoustic force of 16 mN over 20 mm. The same group went on to develop this into a series of acoustic levitation devices, the first of which was reported in the 2014 publication[34] in which *t*wo arrays of ultrasonic transducers were arranged opposite each other to generate a localized standing wave at arbitrary positions utilizing the so called phased-array focusing technique. This technique generates a focal point at a specific position by determining the path difference between the 0th and nth transducers and using the speed of sound within air to find an appropriate time delay as given by the following equation:

$$T_n = \frac{d_n}{c}. \tag{4}$$

By delaying the start of the square wave signal to the nth transducer by this amount, the focal point is generated.

Three advantages were identified to such airborne ultrasound focusing device (AUFD) arrays:

- The particles can be manipulated in all directions according to the movement of the localized standing wave based on the phase-delay control.
- The work space is much larger than those in previous research studies because the ultrasound wave is focused and hence delivered farther.
- The particles are kept trapped even when the acoustic axis is horizontal because the AUFDs provide a sufficient amplitude of ultrasound.

In Ref. 35, the same group utilized four arrays of transducers at 40 kHz or 25 kHz to provide three-dimensional control of expanded polystyrene particles up to 2 mm in diameter, as can been seen in Fig. 1. This work quantified the stability of the movement of the particles by changing the phases of the transducers in 1/16th wavelength (8.5 mm or 13.7 mm for 40 kHz and 25 kHz, respectively) steps, causing the particles to accelerate until they were ejected from the levitation system. The smaller 0.6 mm particles were confined for accelerations of up to 60 m s^{-2} corresponding to approximately 500 μN of force, whereas the 2 mm polystyrene particles maintained entrapment up to 30 m s^{-2} corresponding to approximately 27 mN (both calculated based on F = ma).

The concept of an ultrasonic phased array was further developed by Marzo *et al.*[36] to show that acoustic levitation can be employed to translate, rotate, and manipulate particles using a single-sided emitter array. They also introduce a "holographic acoustic elements framework" that permits the modeling and rapid generation of different traps; however, their work was still light particle rather than liquid drop based.

Developing this approach, Marzo *et al.* showed a wide range of different array structures capable of producing what they termed an acoustic tractor beam in their 2017 article.[37] These so-called tractor beams were shown to be capable of holding millimeter-sized polymer particles and even fruit-flies. Figure 2 shows the different methods used by Marzo *et al.* for generating differing phases from each transducer to produce a focal point for the acoustic field including a physical curved array, flat array with electrically differing phase, and flat array with variable tube length in addition to the

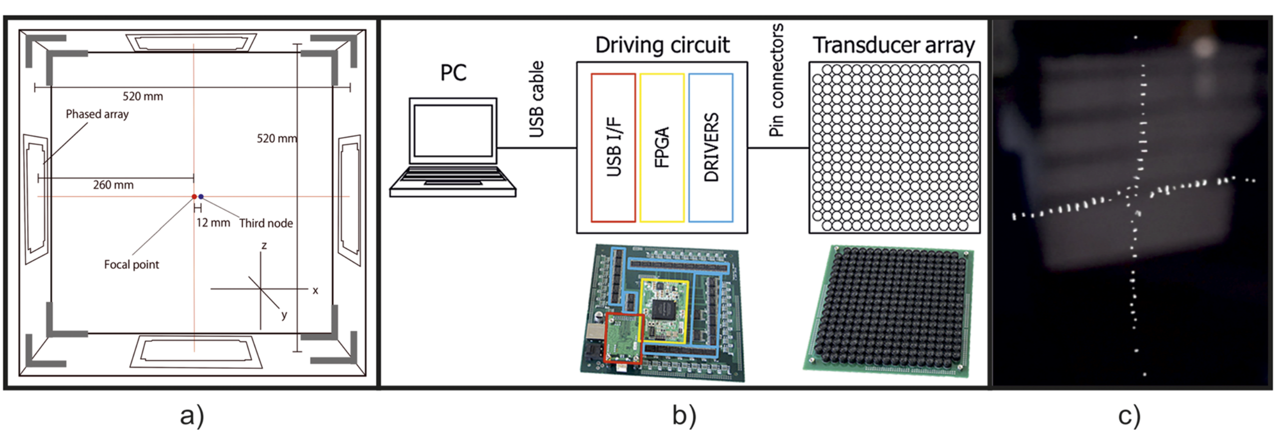

FIG. 1. Use of four arrays configured for three-dimensional control of multiple 2 mm polystyrene spheres. (a) shows relative placement of arrays. (b) shows the schematic of drive and control electronics. A demonstration of suspension of numerous polystyrene beads using the trapping system is shown in (c). Subfigures reproduced with permission from Y. Ochiai, T. Hoshi, and J. Rekimoto, "Three-dimensional mid-air acoustic manipulation by ultrasonic phased arrays," PLoS One **9**(5), e97590 (2014). Copyright 2014 Author(s), licensed under a Creative Commons Attribution 4.0 License, which permits unrestricted use, distribution, and reproduction in any medium, provided that the original author and source are credited.

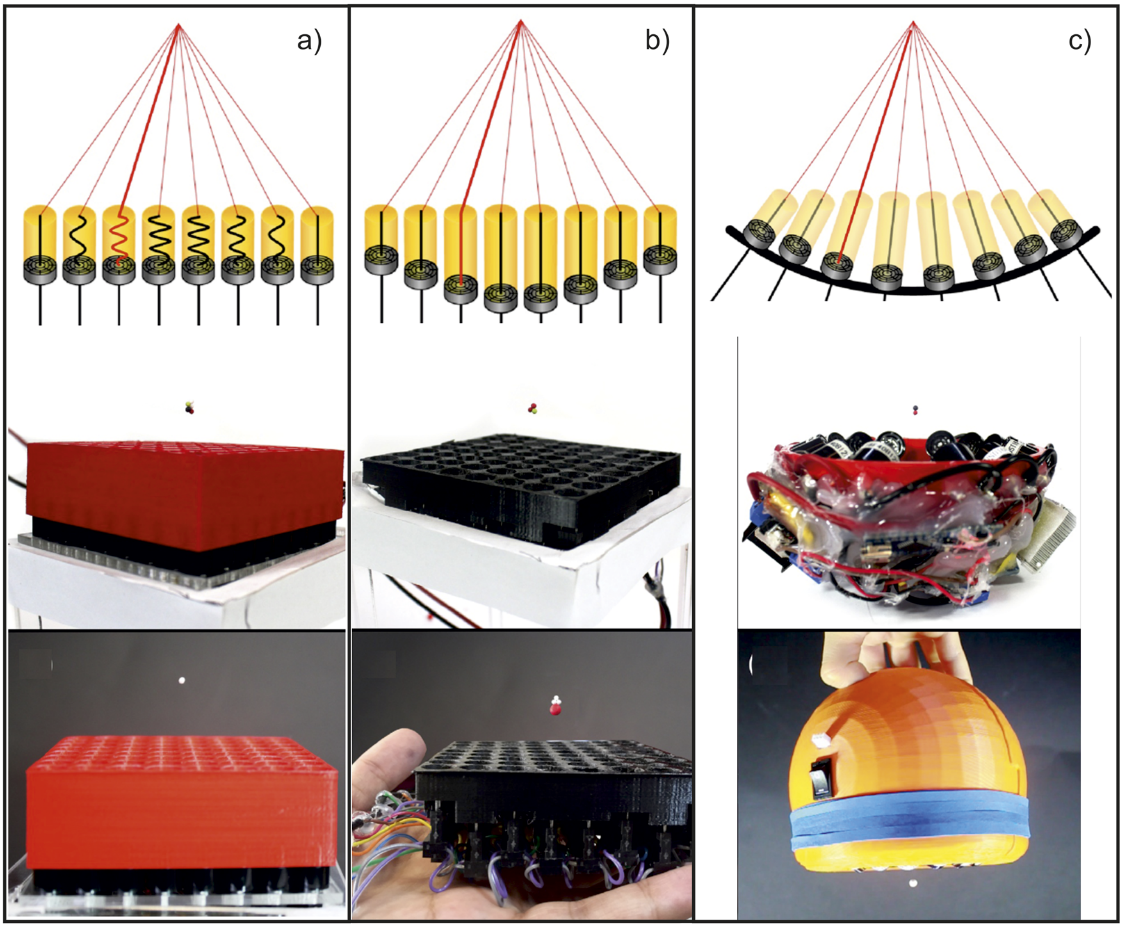

FIG. 2. Realization of various compact single sided acoustic levitation devices utilizing delay lines. Each panel shows a schematic of the approach at the top and two photographs of its use below. (a) Coiled paths to provide phase differences between transducers, (b) straight tubes of varying length to provide phase differences, and (c) the sculpted surface device where focus is achieved with transducers of similar phases. Subfigures reproduced and rearranged with permission from Marzo *et al.*, "Realization of compact tractor beams using acoustic delay-lines," Appl. Phys. Lett. **110**(1), 014102 (2017). Copyright 2017 AIP Publishing LLC.

practical realization of these methods. In this work, it was found that the curved array system was most efficient as the maximum intensity of the transducers was directed toward the target area with minimal losses.

Simulation work in Ref. 38 showcases a novel method of trap generation in order to create 2 or more simultaneous acoustic traps which levitate light spherical particles. This work builds upon that of Marzo *et al.*,[36] simulating a 16 × 16 transducer array which operates at 40 kHz. These simulations form an acoustic trap at position r_1 and a "quiet zone" at position r_2, in which the pressure is comparatively much lower. An acoustic trap at r_2 and a quiet zone at r_1 are then superposed which forms 2 acoustic traps with similar strengths and pressure gradients to suspend light particles.

Marzo *et al.* also developed virtual vortex trapping methods in Ref. 39 to explore the effects of orbital angular momentum on the stability of light polystyrene particles within an acoustic levitator which suspends particles using a vortex trapping motion. It was also found that particles larger than the wavelength of the incident sound were able to be suspended by switching the driver phases, to make the array emit two different pressure fields. The largest particle which was suspended with reasonable stability was a 16 mm expanded polystyrene ball, which had a diameter 1.88 times the wavelength of sound, which in this case is 8.6 mm.

Trajectory control of suspended particles is explored in Ref. 40. In this work, an acoustic levitator consisting of 2 opposing planar arrays with 30 transducers on either side, operating at 40 kHz, was used. Each of the transducers was powered independently and driven with a square wave which had a phase resolution of $\phi = 2\pi/128$, allowing the focal point to be moved as discussed previously. This entire setup was housed within a chamber upon a passive vibration isolation table which limited external air currents and vibrations, respectively. An expanded polystyrene particle was

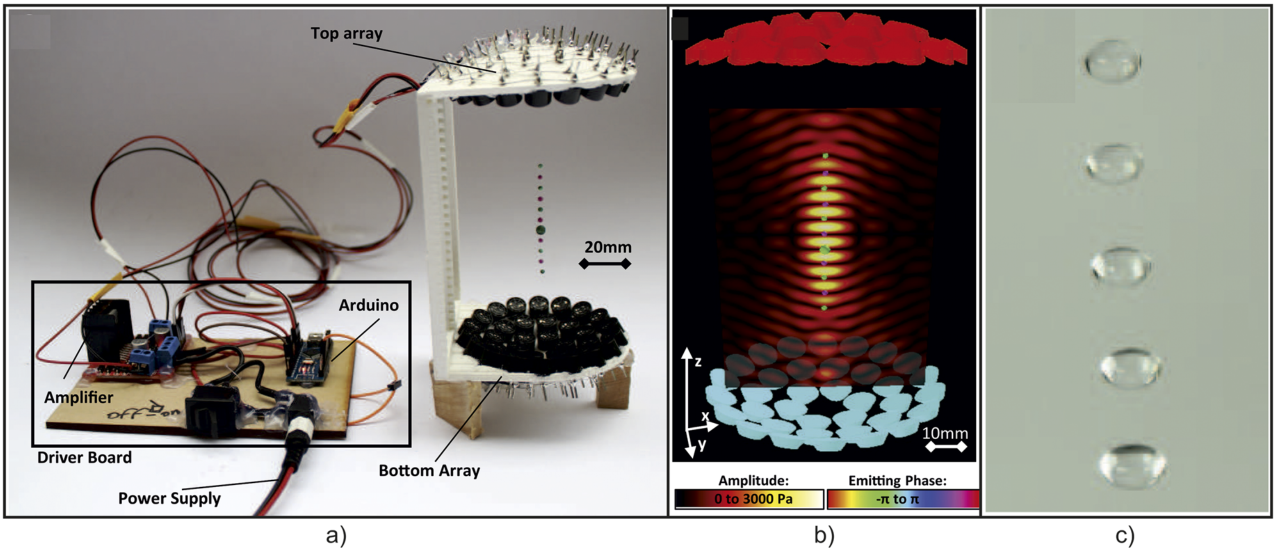

FIG. 3. The TinyLev acoustic levitation system, consisting of the driver board and 72 transducers fixed to a 3D printed twin domed structure, as shown in (a). The simulated acoustic field of such a system is shown in (b). Droplets of water suspended by the TinyLev system are shown in (c). Note their oblate morphology owing to greater vertical trapping forces than those experienced horizontally. Subfigures reproduced with permission from A. Marzo, A. Barnes, and B. W. Drinkwater, "TinyLev: A multi-emitter single-axis acoustic levitator," Rev. Sci. Instrum. **88**(8), 085105 (2017). Copyright 2017 AIP Publishing LLC.

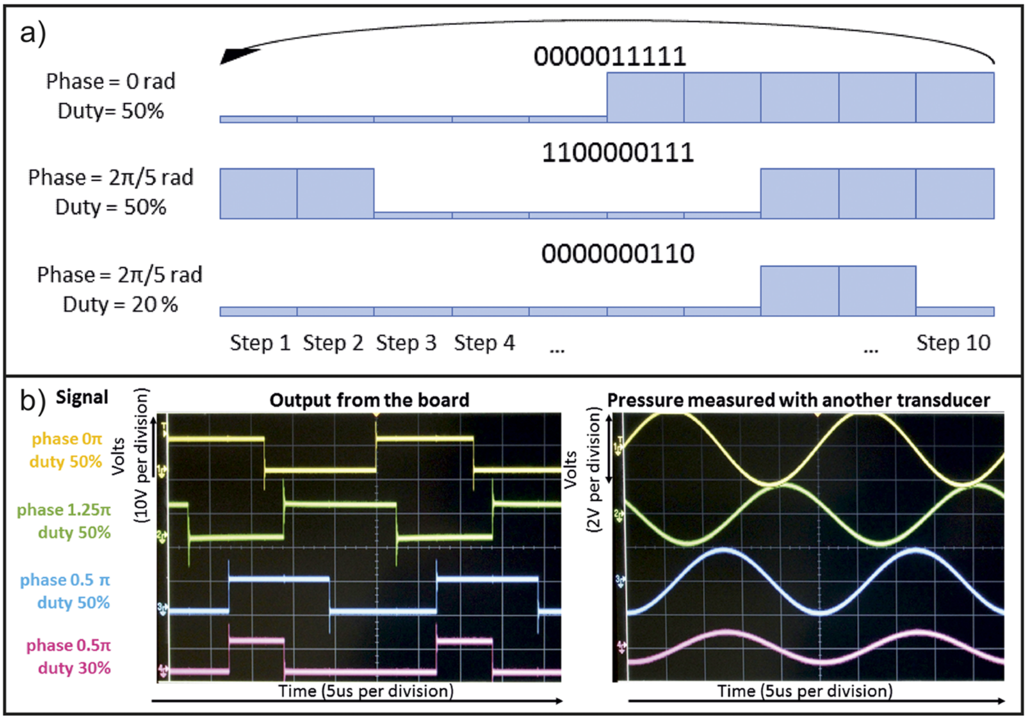

FIG. 4. Signals of the Ultraino system. Phases and duty cycles are controlled by a logic signal which is divided into 10 steps as can be seen in (a). These signals were recorded from the output of the driver board, as can be seen in the left of (b), while the responses measured from another transducer which is used as an ultrasonic microphone are shown in the right of (b). Subfigures reproduced with permission from A. Marzo, T. Corkett, and B. W. Drinkwater, "Ultraino: An open phased-array system for narrowband airborne ultrasound transmission," IEEE Trans. Ultrason., Ferroelectr., Freq. Control **65**(1), 102–111 (2017). Copyright 2017 Author(s), licensed under a Creative Commons Attribution 3.0 Unported License.

tracked through a circular pathway within the x-z plane, by changing the phases of the transducers to move the focal points. It was, however, found that the positions in which the particles reached equilibrium were not those that were desired. Corrections to this pathway were applied by comparing the equilibrium position to the target, and it was found that these corrected pathways were the desired shape assuming that the velocity of the particle was less than 1 cm/s.

Further work by Marzo *et al.*[41] has explored the capabilities of holographic acoustic tweezers to dynamically manipulate multiple particles simultaneously in midair. This is achieved using an algorithm that enables the control of the emitted field from the ultrasonic phased arrays. The two opposing planar arrays consisted of 256, 1 cm diameter transducers on each side, operating at 40 kHz. These arrays were separated by 23 cm. The algorithm is used to generate focal points at the position of the particles before controlling the transducer phases to move the foci. The minimum distance between adjacent particles was 1.3 cm as closer traps merged and inhibited independent control of the 25 total traps. Twin traps were generated in order to control the orientation of asymmetric particles. These were, however, found to be insufficient to suspend the particles; thus, rapid switching between twin traps and focal points was used to orientate and suspend particles. An example of the acoustic field of a twin trap system is shown in Fig. 5.

THE LIQUID LEVITATION ERA BEGINS

A major turning point in the application of acoustic levitation was reported in Ref. 11 building on the work in Ref. 37 but including two curved arrays facing each other. This heralded a new era of acoustic levitation allowing low cost levitation of liquid samples. While still employing the low-cost transducer array, one significant feature of this work was to use low cost Arduino microcontrollers, making it possible for anyone capable of using a soldering iron to produce a viable acoustic levitation system. The details of the design and software were made available in the form of an Instructable[42] bringing levitation to the masses. Figure 3 shows the TinyLev system and examples of levitated objects including liquid drops. This system was able to levitate objects of much higher density than expanded polystyrene balls, including pieces of ceramic, sugar, and sapphire spheres.

In Ref. 43, Marzo *et al.* present a package called Ultraino which they describe as a modular, inexpensive, and open platform that provides hardware, software, and example applications specifically aimed at controlling the transmission of narrowband airborne ultrasound. The aim of this was not only to provide a fixed design example but to allow users to define their own problem and using the supplied modeling software to predict the most appropriate array

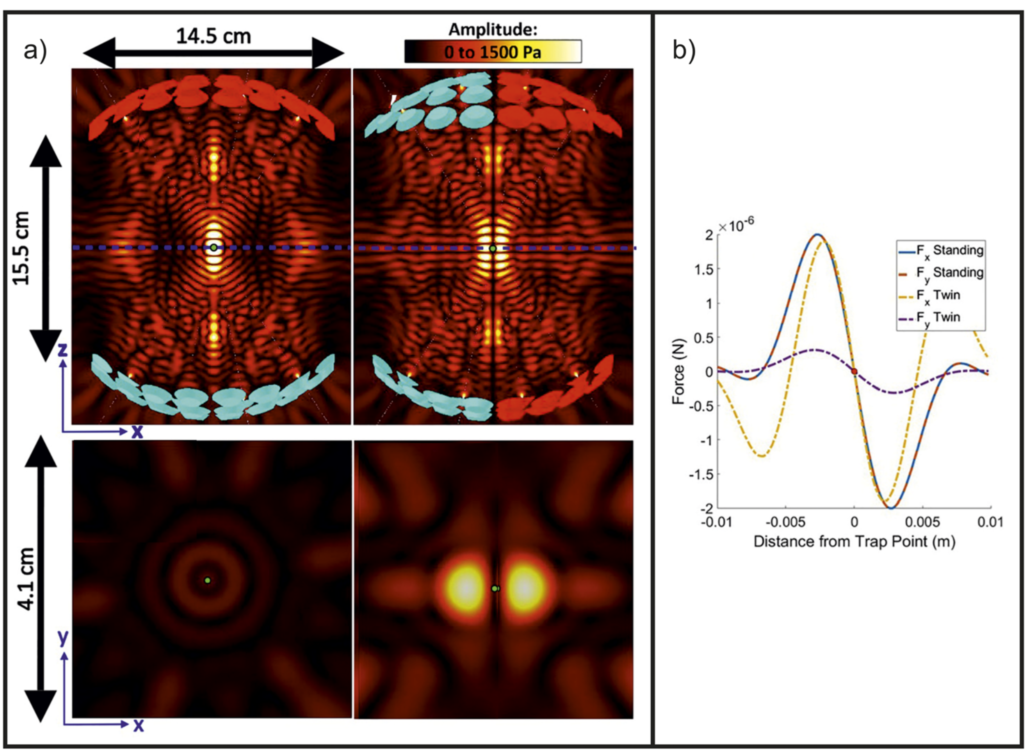

FIG. 5. The acoustic field of the so-called acoustic lock system in its multiplexed states is shown in (a) where the left images are the standing wave field and the right images show the twin trap field from the side and above in a plane which transects the central trap. The blue lines indicate the planes of the lower images. The force in the vertical and horizontal directions is shown in (b) for both of the multiplexed states. The central trap is represented as a red dot. Subplots are reproduced with permission from Cox *et al.*, "Acoustic lock: Position and orientation trapping of nonspherical sub-wavelength particles in mid-air using a single-axis acoustic levitator," Appl. Phys. Lett. **113**(5), 054101 (2018). Copyright 2018 AIP Publishing LLC.

configuration. Well-defined hardware building blocks can then be used to allow the configuration to be implemented. The realization that low-cost transducers could be driven by an amplified logic signal with variable phase and duty cycle has transformed the feasibility of phased arrays, and in Fig. 4, we show examples taken from Ref. 44. It should be noted that, even for Ultraino, liquid levitation data were only presented for a two-sided standing wave system similar to the TinyLev and not for any of the single sided configurations which lack the confinement needed for high density samples. One well known phenomenon in single axis acoustic levitation is that the samples are prone to spinning. In many cases, this is not significant, but where samples are nonspherical, such as insects, or where liquid crystal structure is to be determined, this is an important factor which must be considered.

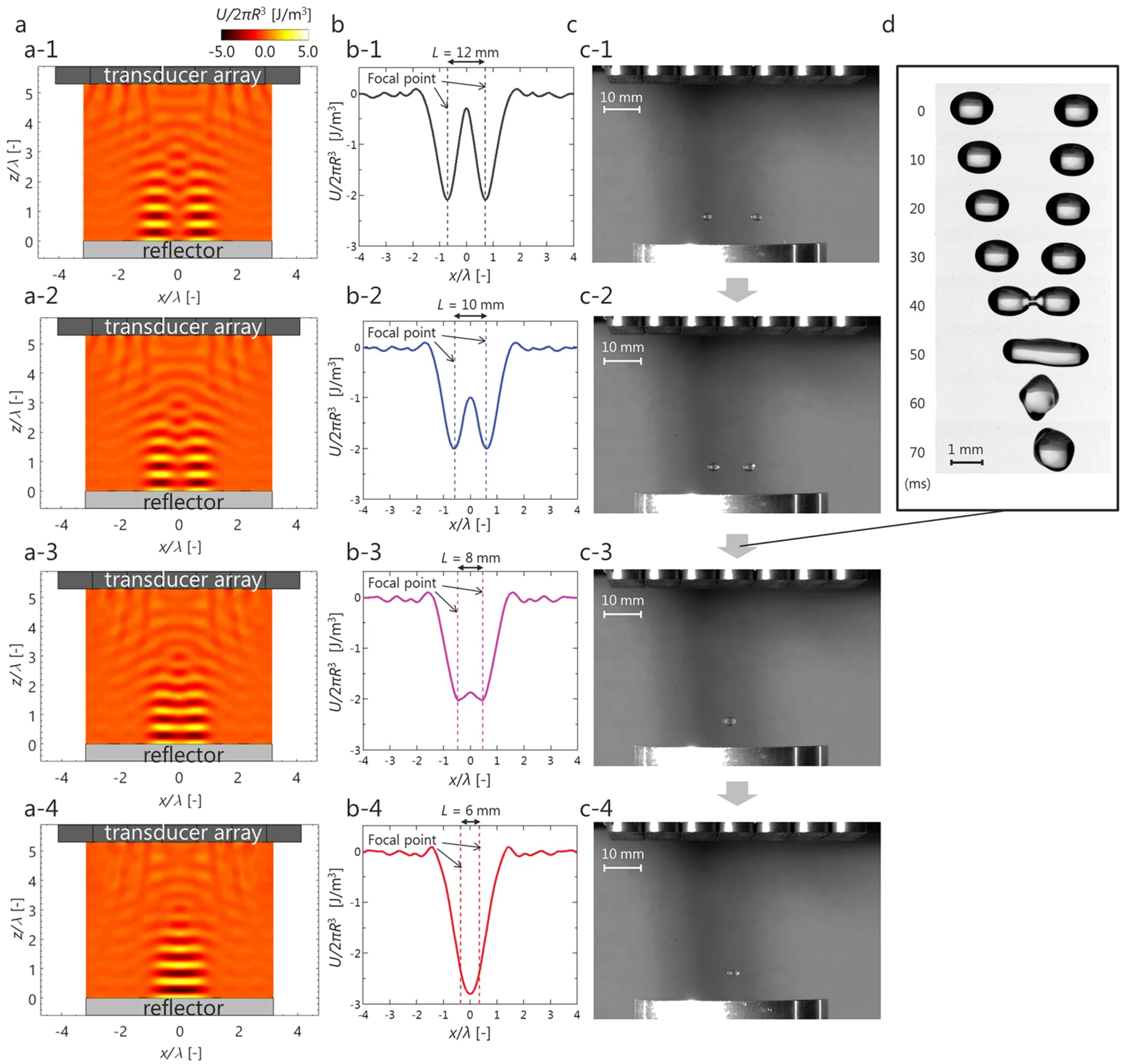

FIG. 6. Noncontact translation and coalescence is achieved using time variable acoustic fields. The acoustic potential of the transducer array and reflector combination can be seen in (a), while (b) shows the acoustic potential as a function of x. Photographs of the droplets within the focal points above the reflector can be seen in (c). A time series of the coalescence is shown in (d). The two focal points are moved toward the central position with each iteration. Reproduced with permission from A. Watanabe, K. Hasegawa, and Y. Abe, "Contactless fluid manipulation in air: Droplet coalescence and active mixing by acoustic levitation," Sci. Rep. 8(1), 10221 (2018).[43] Copyright 2018 Author(s), licensed under a Creative Commons Attribution 4.0 License.

In Ref. 44, a variation on the single axis levitator system was reported that saw each transducer "bowl" divided into two symmetric halves with an invertible phase to facilitate the emission of both vertical standing waves and twin-traps, where the confining force is also applied laterally. It was shown that the system could stop the rotation in the supplementary video of Ref. 44 showing the effect on solid objects and by way of example insects. There are no data presented within the manuscript for liquid levitation although it has been shown in the supplementary material of Ref. 44. This system provides the ability to trade-off the lateral stability for the levitation of denser materials. Thus, lower density samples, such as insects, may be held in a more stable position than samples such as acrylic or wooden cuboids.

FROM BASIC HARDWARE TO LIQUID DROP APPLICATIONS

In Ref. 45, a rectangular ultrasonic phased array was combined with a reflector surface to demonstrate contactless coalescence and mixing techniques for droplets in air. The array was designed to have two focal points, generated by switching at 500 Hz between the two (since all transducers are used to form the two traps). The distance between the two focal points could then be reduced to produce a single large standing wave resulting in coalescence of the droplets within a single trap. Figure 6(a) shows the estimation of the acoustic potentials, the resulting potentials at the pressure nodes, and images of two water drops being brought together and coalescing.

Shen *et al.*[46] had previously demonstrated oscillation modes in a "conventional" single-axis acoustic levitator forming a standing wave between the emitter and the curved reflector by modulating the amplitude by up to 10%. They swept the modulation frequency upward with increments of 0.5 Hz and observed different oscillation modes being excited. Watanabe[45] implemented a similar scheme in the phased array and compared mixing performance between cases with and without mode oscillation and showed that the flow induced by mode oscillation promotes droplet mixing (an example of which

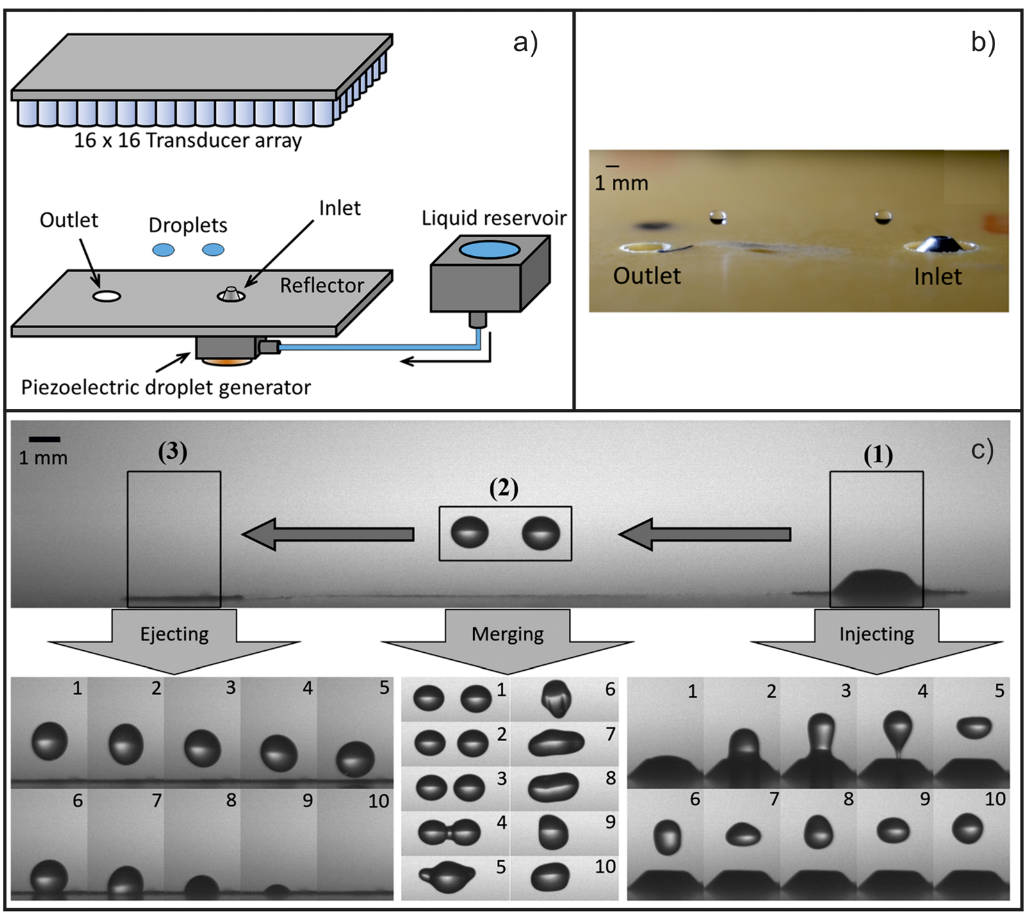

FIG. 7. (a) shows a diagram of the acoustic levitation system consisting of a 16 × 16 transducer array and a planar reflector. Liquid is drawn from the reservoir and into the system via a piezoelectric droplet generator. The droplets are ejected from the system by moving them to above the outlet and switching off the acoustic field. (b) shows a color photograph of the inlet and outlet with two droplets being transported between. (c) shows a series of images of the droplets being injected (1), merged (2), and ejected (3). Subfigures reproduced with permission from M. A. Andrade, T. S. Camargo, and A. Marzo, "Automatic contactless injection, transportation, merging, and ejection of droplets with a multifocal point acoustic levitator," Rev. Sci. Instrum. **89**(12), 125105 (2018). Copyright 2018 AIP Publishing LLC.

TABLE I. Comparison of the current state of the art for key parameters between Langevin and transducer arrays.

Parameter	Langevin	References	Transducer array best	References
Power	130 W	10	5 W	11
Frequency/wavelength	25 kHz	51	28 kHz, 40 kHz	Various
Wavelength step	n/a	n/a	$2\pi/128$	40
Maximum sample size	50 mm	51	16 mm	39
Acoustic force	12 mN	51	27 mN	35

is shown in Fig. 6) which effectively brings this technique into a useful tool for containerless chemistry.

In *Automatic contactless injection, transportation, merging, and ejection of droplets with a multifocal point acoustic levitator*,[46] Andrade *et al.* used a 16 × 16 array of 40 kHz ultrasonic transducers, a distance of 110 mm away from a plane reflector which along with the superposition of the incident and reflected waves formed a standing wave with a series of pressure nodes where liquid droplets could be trapped and moved in two dimensions above the surface. The reflectors' position was chosen by focusing the transducers to different positions and empirically determining which distance provided the largest pressure amplitude.[47] Their system had an integrated droplet injector inserted in the reflector including a piezoelectric buzzer and a 1 mm diameter nozzle. When a voltage pulse was applied, a droplet was injected and trapped at the bottom pressure node of the standing wave. The droplet outlet was a simple hole in the reflector, and switching off the acoustic field allowed the drop to pass through under gravity. Figure 7 shows the injection of two droplets followed by the merging and subsequent ejection.

NEW PERSPECTIVES—THE FUTURE OF ACOUSTIC LEVITATION OF LIQUIDS

There was a mention in the supplementary material of Ref. 44 of the levitation of liquids. This made important reference to the shape of the resulting confined droplet: it was found that the droplet formed an approximate ovoid and the boundary of the liquid appeared less smooth. In the move from levitation of solids such as polystyrene balls which have relatively fixed morphology, to fluids which conform to their confinement, the shape of the produced acoustic fields has become increasingly important. For many experimental systems, this is simply a feature of the acoustic field which limits the size of droplet that can be confined. In sample presentation scenarios, however, the shape of the droplet can be an important factor which directly impacts the results. Consequently, there is an increasing shift from awareness toward control of droplet shape by balancing the confinement potential of the acoustic field against the forces applied to the droplets to maximize sphericity; for example, in Ref. 48, the droplet sphericity as a function of voltage applied to the TinyLev system was determined and optimized to balance these key parameters.

In recent publications such as Ref. 48, this new era of low-cost phased array ultrasonic levitation devices are beginning to find use in sample presentation to noncontact measurement techniques in applications previously making use of Langevin horns.[49] This facilitates containerless, background free spectroscopy which ushers in a new wave of experimental techniques and brings with it significant advantages in terms of measurement resolution without imparting significant energy into the sample. Although further developments are required for these techniques to become universally applied, it is clear that sample presentation systems based on acoustic levitation are likely to become as ubiquitous as pipettes are now in fluidic analysis over the coming decade.

To our knowledge, there are currently no truly single sided systems which can reliably confine nonrigid samples such as fluid droplets, owing to the limited transverse acoustic forces. This represents one of the clear directions for future developments to produce complex acoustic fields which have improved transverse fields for fluid entrapment. Advances in microcontroller systems, capable of smaller wavelength fractions, will be a key enabler of such developments, allowing for realistic implementation of arbitrary acoustic fields. The final element which will provide scope for further improvement is the availability of acoustic transducers specifically engineered for such purposes. The limitations in absolute output power, frequency, and physical size are largely governed by mass production for other applications such as range finding. Recent developments toward customized transducers[50] will allow for better control of these parameters yielding better control of wavelength and permitting systems to be tailored to specific sample sizes of interest. In combination with sample manipulation processes such as those presented in Ref. 45, such developments will allow for sample preparation and presentation to almost all spectroscopic measurement techniques.

SUMMARY

In this review article, we have summarized the current state of the art of acoustic levitation of liquids using low cost transducer arrays. In Table I, we briefly summarize the current state of the art for each of the key parameters which dictate the levitation performance. The maximum sample size is for nonliquid samples and is presented as the size which may one day be achievable. These parameters are then compared to a traditional Langevin system.

CONCLUSION

The realization that low-cost transducers could be driven by an amplified logic signal has transformed the feasibility of phased arrays. Through field programmable gate arrays (FPGAs) or simple microcontrollers, a large number of transducers can have their signals tailored in a cost-effective way to produce a given pressure field profile. Commercial companies such as Pixie Dust Technologies[52] and Ultrahaptics[53] offer customers bespoke phased array packages, primarily for midair tactile transducers. This review has focused on the development of ultrasonic phased arrays although alongside there have been developments in single transducer levitation through the use of acoustic hologram reflectors[54] and transmission "metamaterial bricks."[55] We have presented an expected future direction of the technology based on the current direction, but it is clear that we are witnessing the start of a new era of containerless sample preparation and presentation.

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