TinyLev: a Robust Non-resonant Single-axis Acoustic Levitator.

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Acoustic Levitation has the potential to enable ground-breaking discoveries due to its ability to hold a wide variety of substances under container-less conditions. It has found application in spectroscopy, chemistry or the study of organisms in microgravity. Current levitators are normally constructed using Langevin horns that need to be manufactured to high tolerance with carefully matched resonant frequencies. This resonance condition is hard to maintain as their temperature changes due to the output powers required. In addition, they are also required to operate at high voltages which may cause problems in humid and challenging experimental environments. Here, we design, build and evaluate a single-axis levitator based on multiple, low-voltage, well-matched and commercially available ultrasonic transducers. The levitator operates at 40kHz in air and can trap objects of up 2.2 g/cm^3 density and 4mm in diameter while powered with 10 Volts and 1 Ampere. Levitation of water, fused-silica spheres, small insects and electronic components is demonstrated. The device is constructed from low-cost off-the-shelf components and is easily assembled using 3D printed components. Complete instructions are provided on how to assemble the levitator and the device can be adapted easily for specialist use.

Introduction

Sound is a mechanical wave and as such it carries energy that can push particles due to acoustic radiation forces [king34, gorkov62, doinikov96, bruus12]. When the forces exerted on an object are strong enough and converge from all directions, the particles can be levitated and stably trapped [brand01].

Acoustic Waves can trap particles of different materials and a wide range of sizes. This is a significant advantage over optical trapping in which the particle size must be in the order of micrometers and the materials should be dielectric or transparent [Neuman04]. Also, acoustic trapping has a ratio of trapping force to input energy orders of magnitude higher than optical manipulation [Baresch13]. Other forms of levitation such as magnetic levitation only support ferromagnetic samples [Hajjajji09], in aerodynamic levitation [yarin97] the samples are agitated and altered in the process, and in electrostatic levitation [mauro11] the systems are complex and the sample materials limited.

The versatility of airborne acoustic levitation makes it a useful tool in pharmaceutics [webber11], nano-assemblies [roesler16] and the levitation of biological samples [puskar07] or even small animals [xie06][sundvik15]. Acoustic levitation of liquids can be used to measure their surface tension [tian95] or the rheological properties of surfactant solutions [Tian95]. Other applications include the formation of levitated ice flakes [bauerecker98], eutectic crystal growth in molten metals [xie02], evaporation of binary liquids [yarin02], the study of materials phase transitions [ermoline04], and the rapid crystallization [cao12] or ionization [stind13] of samples. Levitated samples do not need to be in a receptacle, providing benefits in accurate spectroscopic methods [santenson03] for algae [wood05], blood cells [puskar07] or droplet aggregations [schenk12]. In general, acoustic levitation is a useful and versatile tool in fundamental and applied biomaterials research [weber12].

The most common arrangement for acoustic levitators is a single-axis configuration [whymark75]. There are two main types of single-axis levitator. The first is based on an acoustic transducer and a reflector, the distance and shape of those are designed as a resonant cavity. On the other hand, non-resonant levitators are made of two separated emitters. Resonant devices are more efficient but are sensitive to changes in temperature and arrangement of the elements. Both resonant and non-resonant levitators are driven with a sinusoidal excitation signal to generate a standing wave between their elements, this standing wave will trap particles at its nodes.

For resonant levitators, it was shown that a concave reflector was better than a planar one [oran80] and that using a large radiation plate attached to the front of a Langevin horn emitter provided more stability [trihn85] allowing the levitation of liquids and study of samples in microgravity; these results have been validated in multiple research works [xie01][xie02]. Change in temperature affects the speed of sound and thus detunes the resonance and reduces trapping strength [xie03], also introducing large samples in the levitator shifts its resonant frequency [xie07], leading to the need to adjust the system (e.g. the cavity size). Using also a concave emitter increased significantly the efficiency of the levitators [Andrade10], by locally concentrating the acoustic energy. Further efficiency improvements can be obtained if the non-linear behaviours are analysed [Andrade14]. For improving the adaptability of emitter-reflector levitators a morphing reflector made of water or elastic materials can be used [hong12][foresti15].

For a versatile and more stable levitator researchers rely into non-resonant systems using for instance two emitters opposed to each other [Webber09]. Using this approach, a levitator with an operating temperature range of -40 to 40°C was developed that required no distance calibration between the two opposed emitters.

All these previous levitators are based on single or opposed pairs of Langevin horns [Lin95] which are made of piezoelectric disks clamped between a backing material and a resonating horn. They have the advantage of supporting high-voltages (typically 100-1000 V) and thus generating high acoustic pressure with only one element. However, they have several disadvantages that limit their widespread use. Firstly, Langevin horns are hard to tune to the desired resonant frequency, for instance Webber et. al [webber09] reported that dozens of horns are built to find the two with the closest frequency. Secondly, the high-voltage required to drive them is potentially dangerous, not ideal in humid environments and increases the cost of the electronic components. Thirdly , they are sensitive to temperature, requiring them to warm-up before use or losing effectivity after intense functioning.

On the other hand, phased arrays made of hundreds of ultrasonic transducers have been demonstrated to levitate small electronic components [OchiaiTOG]. However, their capability to levitate liquids is still unproven and current phased-arrays require complex custom electronics available only to a few research laboratories [Shinoda][Marzo15][OchiaiTOG].

Here, we present TinyLev, a single-axis non-resonant levitator made with off-the-shelf low-cost components (Figure 1). This levitator is stable, robust to temperature, non-dangerous and easy to operate. Instead of using one or two Langevin horns, we used 72 simple ultrasonic emitters. This is an analogy to the translation from a single powerful lamp to an array of LEDs that is being seen in, e.g. traffic lights, projectors and spotlights to make devices inexpensive, durable and reliable. In the following section, we show the procedures followed to design TinyLev and evaluate its performance.

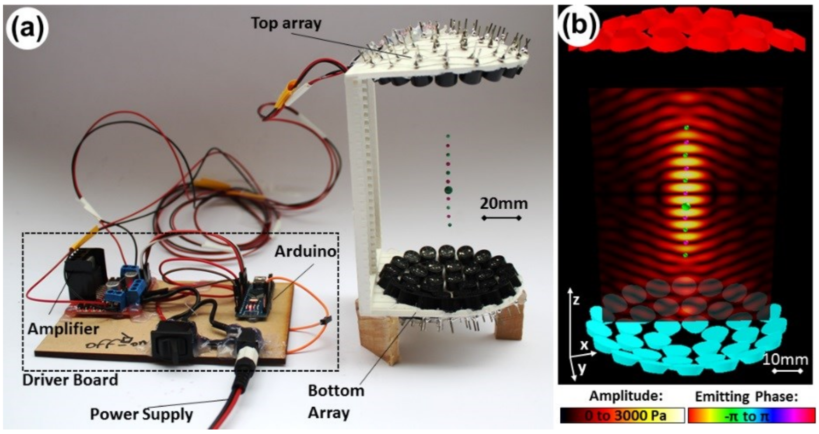

Figure 1. a) TinyLev system composed of the driving board and the single-axis levitator with 72 transducers. Expanded Polystyrene (EPS) particles are trapped at its nodes. b) simulated acoustic field. Each circle represents a 10mm diameter transducer and the colour represents the phase.

Design

We will describe the design considerations for making a single-axis levitator using an array of small ultrasonic emitters. Firstly, we analyse the available transducers which are the elements that transform the electric signal into acoustic power. Secondly, we study how to spatially arrange the transducers to maximize trapping forces and working area as well as reducing reflections. Thirdly, we present low-cost and effective electronics to drive the transducers.

Field and force simulations

For simulating the generated complex acoustic pressure by each transducer, we used the piston source model [ONeil49], the contribution of each transducer can be summed to get the total field. To characterize a transducer constant power and the piston radius is needed; the power constants can be found in Table 1, the radius of the piston was always 4.5mm. The force was calculated as the gradient of the Gork'ov potential [gorkov54]. More details of the method can be found, for example, in [Marzo15] and in the Supplementary Information. We note that there is an additional effect due to reflections that is not considered by this method. However, as it will be seen later, the reflected amplitudes in the device are small and hence may be neglected in the first approximation. The low negligible influence of reflections is also supported by the good correspondence between the simulated and experimental levitation force (Figure 7), the small difference in current consumption at different phase differences between the halves (Supplementary Information), and the ability to move the levitated samples across several nodes (Supplementary Movie 1).

Transducers

The main component of the levitator are the transducers, elements that transform the electrical signal into acoustic waves. For operating in air transducers for distance measurement provide the best ratio of acoustic power to surface and price. Most of the commercially available transducers operate at 40kHz. Using 40kHz represents a wavelength of 8.5mm in air which allows the levitation of samples of up to 4mm (half-wavelength).

The commercially available transducers we have studied are listed in Table 1. We have evaluated them according to several factors repeating the measures for 10 transducers. The transducers were fed with a square-wave of 10Vpp (Agilent 33210A) and measured with a wideband microphone (1/8" Brüel & Kjær calibrated microphone Type 4138-A-015) positioned 20cm away. Power is the pressure that they generate at a fixed distance under the same excitation signal. Another important measure is the phase standard deviation, sometimes transducers have small differences in their manufacturing that makes them output slightly offset signals even if they are fed with the same signal and within the same distance. In Figure 2, we show how the RMS phase-deviation of the transducers affects the trapping force of the device shown in Figure 1.

Most of the transducers are available in either 10mm or 16mm diameter. We decided to use 10mm to make the device as compact as possible, and obtain more power per area (MA40S4S $0.17/\pi 5^2$ > MSO-A1640H10T $0.36/\pi 8^2$). The Murata transducers are the best option for 10mm with more power and less phase deviation; however, the Ningbo or Manorshi 10mm transducers minimise cost and would only incur in a 3% reduction in trapping force due to their phased deviation.

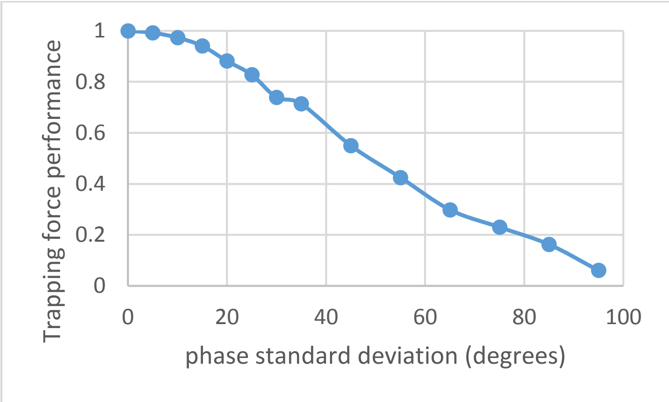

Figure 2. Simulation of the trapping force performance depending on the phase standard deviation of the transducers.

Number of transducers

After exploring some of the possibilities we decided to use 36 transducers at each side (72 in total) arranged in rings of 6, 12 and 18 which comes from the optimal circle packing in a hexagonal pattern (Supplementary Information). As it will be seen later this quantity of transducers generates enough force to levitate samples of interest and keeps the manufacturing process simple and the cost low. Adding more rings of transducers would require a bigger separation between the arrays and make the device resonant.

Arrangement of the transducers

Langevin-horn levitators radiate sound with large-surface horns or curved reflectors that naturally focus the acoustic power. In contrast, TinyLev is made of arrays of small transducers that achieving an acoustic focus by their orientation and distance. We analysed 4 focusing strategies as shown in Fig. 3. Laying the transducers in flat surfaces allows for a very simple laser cut base-plate but the trapping force is too low for most applications (i.e. 2% of the trapping force performance compared to the best configuration). It is possible to focus the acoustic energy of an array by electronically delaying the phase of the signals with 50% performance but we want an affordable and simple levitator so we will only use one or two driving signals. It is still possible to introduce static phase-delays by placing the transducers at fixed distances from the centre [marzo17], this strategy lead to focusing 50% performance. The best performing configuration (100%) is achieved by placing the transducers within the same distance to the centre and pointing towards it .

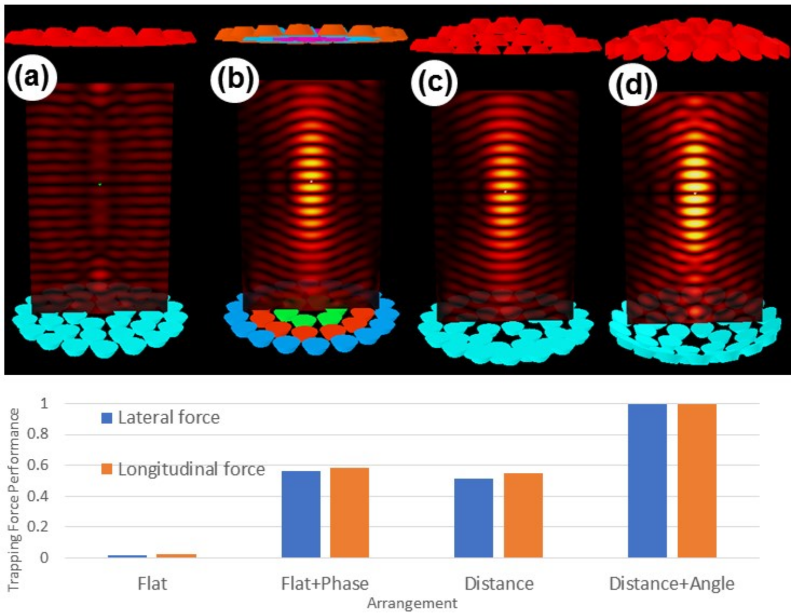

Figure 3. Different arrangements for focusing the acoustic field: a) no focusing, b) phase focusing, c) focusing by distance, d) focusing by distance and angle. Scale is the same and each circle represents a 10mm diameter transducer. Bottom) normalized trapping forces obtained with each arrangement.

The separation of the transducers also affects the trapping forces that the device generates. In Figure 4, we show the trapping forces generated depending on different transducer separations. Note that the z-force needs to be highest as it provides the levitation force, the x and y forces may be smaller but provide lateral stability.

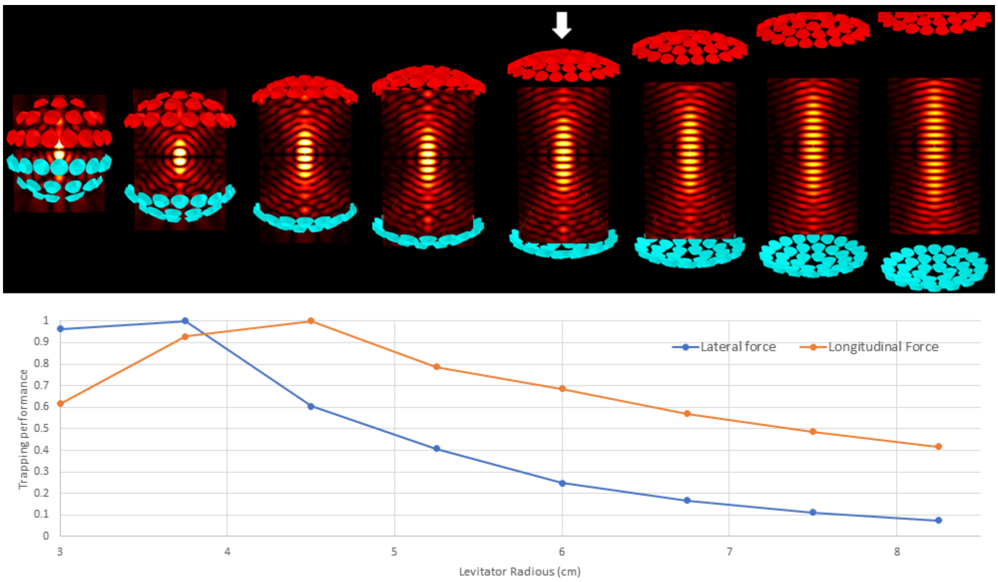

Figure 4. Lateral and longitudinal trapping force depending on the levitator radius. The same amount of transducers are used and they are packed as tightly as possible. The forces are normalized. Scale is the same and each circle represents a 10mm diameter transducer.

To manufacture the frame in which the transducers will be mounted we analysed various options. We selected 3D printing since it is becoming an available manufacturing process and permitted to obtain accurate sockets for the transducers that fix their position and angle. 3D printing the frame in one piece provides stability and simplicity. The only way of 3D printing the frame in one piece is laying in the bed with the bowls pointing upwards (Figure 5). This limits the achievable curvature of the bowls as otherwise there will be too much overhang. Although, the maximum longitudinal trapping force was obtained with a radius of 4.5cm, we selected the arrangement with 6 cm radius to minimize overhang, reflections and obtain more functional traps.

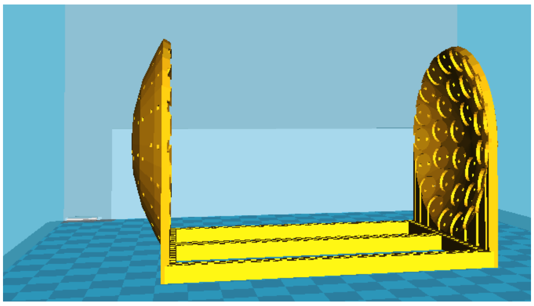

Figure 5. Placement of the base in the 3D printer. This position allows to print it without support but limits the maximum curvature of the bowls.

Driving electronics

We decided to use square waves since they are easier to generate compared to sinusoidal waves. Feeding transducers with square waves is a common practice [Seah][Marzo] since the transducers have a resonant behaviour, the output is still sinusoidal. In the supplementary information we show the excitation signal and the corresponding transducer output for both a sinusoidal and the driver excitation signal.

We used an Arduino Nano to generate the logic signals and a L297N motor driver to amplify the signals. We use a push-pull configuration so the peak-to-peak voltage that the transducers receive is double the input voltage. The electronics can drive two channels with up to 70Vpp and a phase resolution of $\pi/12$. One channel is kept at a constant phase while the other channel's phase can be increased or decreased to move the samples upwards or downwards. More information and schematics are provided in the SI and SI movie.

Results

Trapping force.

The main feature of the levitator is the maximum density of the particles that it can levitate. If the particles are in the Rayleigh regime (smaller than half the wavelength) then the trapping force is proportional to the volume so the particle size is irrelevant and only the density limits the samples. In Fig. 7 we show the required voltage for samples of different densities, i.e. Isopropyl (0.79 g/cm^3), water (1), sugar (1.5) and fused silica (2.2).

Although some samples were liquids, before the dropping their shape was spherical. The densest particle was the MOSFET which does not match the simulations as well as the rest. We hypothesized that it is because its shape was irregular and the levitator was operating above its 20Vpp maximum. Some of the levitated samples are shown in Fig. 8.

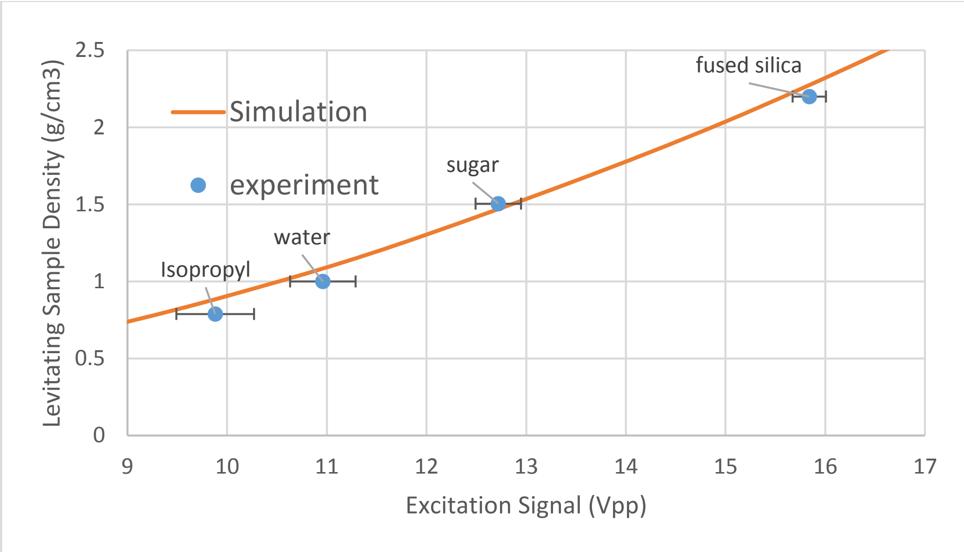

Figure 7. Minimum excitation voltage for levitating samples of different densities. The experiments were repeated 5 times.

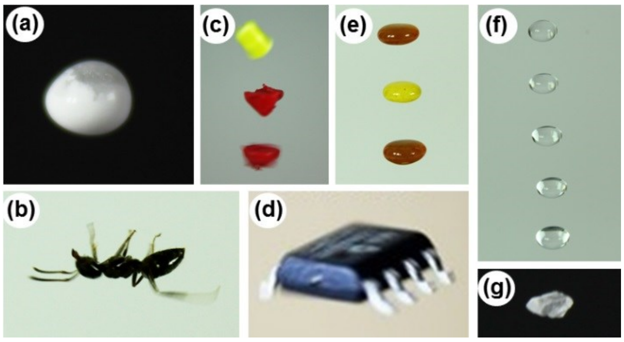

Figure 8. Levitated Samples. a) A 40µl supersaturated solution of Isopropyl and Tin Dioxide, 2.5mm in diameter. b) ant, 6mm long without the antennas. c) Polylactic Acid, 2mm width fragments. d) MOSFET TC4427, 5x1.45x3.85mm. e) ketchup and mustard, 3mm wide. f) water, 3mm wide. g) sugar crystal, 1mm wide.

Robustness of the levitator.

Tests with the levitators suggested that it was easy to use and required no setup. Continuous levitation of solutions for more than 2 hours is shown in the Supplementary Information, with experiments measuring the evaporation rate of sugary water and jelly. Similarly, the evaporation was accelerated by placing a soldering iron at 5mm from the sample.

Conclusion

We have presented TinyLev, a single-axis non-resonant acoustic levitator capable of holding samples of interest in mid-air. The difference with previous work is that it is made of an array of small speakers instead of a single powerful transducer. This reduces the cost and simplifies the manufacture process so that anyone can manufacture it using readily available components. Although the maximum density in normal operations regime was 2.2g/cm^3, it will still enable analysis of most of the biological and liquid samples. We believe that this work is a democratization of acoustic levitation, a technology with enormous potential for multitude of applications (e.g. biotechnology, chemistry or spectroscopy) but previously constrained to a few research labs. We hope that TinyLev helps more research labs or schools to have access to acoustic levitation.

Acknowledgments

References

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