University *of Ljubljana*
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Seminar Ib - 1. letnik, II. stopnja

Acoustic levitation

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Abstract

In this seminar one dimensional acoustic levitation is presented with two distinct approaches, near-field levitation and standing wave levitation. Description of latter is restricted for enough small (solid and liquid) particles. For analitical description for standing wave levitation approach, known as King‘s, is used, later acoustic potential is presented and viscous corrections are described. In last section, description of acoustic levitation is extended to its applications.

Contents

1 Introduction

Levitation is a process in which an upward force(s) counteracts downward gravitational force of an object so that there is no physical contact between levitated object and ground and object is found in a stable position. Levitation can be accomplished with five different techniques ([1]), according to different levitating forces: magnetic, electric, optical, aerodynamic and acoustic.

In this seminar (one dimensional) acoustic levitation will be presented more closely. Acoustic waves are mechanical waves that can only propagate through physical medium. These waves scatter on obstacles and transfer some of their momentum on obstacles, creating force. This force can also be seen as consequence of radiation pressure and is relatively small but it can become sufficiently large to overcome gravity force. Usually waves with high intensities and frequencies in ultrasonic range of spectrum are used (above 20 kHz) so this technique of levitation is soundless for human ears.

Advantage of acoustic levitation compared to other mentioned techiques is the fact that it has no material limitation. Electric levitation for example is most achievable with conductive materials.

2 Near-field levitation

Near-field levitation (also known as squeeze film acoustic levitation) is one of two different configurations of acoustic levitation. It can be observed by placing object with planar surface just above a sound radiator (or transducer - converter of electric energy to sound vibrations). Between radiator and object is a thin layer of air. Planar object acts as an obstacle from which sound waves with high intensity emitted from radiator are reflected. Distance between sound radiator and object is much smaller compared with wavelength of sound λ (several μm compared with $\lambda \sim$ several mm). As a consequence standing waves can not be created.

For simple description of near-field levitation we use a model which assumes ideal gas and conservation of mass of air trapped in the gap ([1], [2]). Regarding these conditions we can use adiabatic assumption for air layer $pV^{\kappa} = const$. Since we are considered in only one dimensional

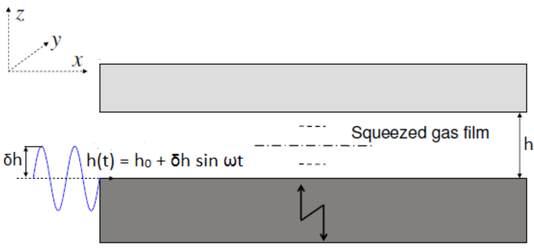


Figure 1: Sheme of near-field levitation sistem. [2]

levitation, we can write

$$ph^{\kappa} = const. \tag{1}$$

where h denotes height on z-axis on which levitated object is found (vertical size of the gap). Air in the gap is squeezed and released because of sound waves. Radiator oscillates while object does not. This oscillation causes also size of the gap h to oscillate:

$$h = h_0 + \delta h \; sin\omega t \tag{2}$$

where δh stands for amplitude of oscillations. As it can be seen on the graph $p(h)$ (Fig. 2) harmonic oscillations of h create non-harmonic oscillations of pressure within the gap due non-linearity of adiabatic relation. Corresponding pressure to position h_0 is p_0 but while h_0 is also average value of oscillatory h, p_0 is not average value of oscillatory pressure. Average pressure in the gap $\langle p \rangle$ exceeds surrounding pressure p_0 due nonlinearity of adiabatic relation. This difference between pressure in the gap and the pressure around our system is what creates levitation.

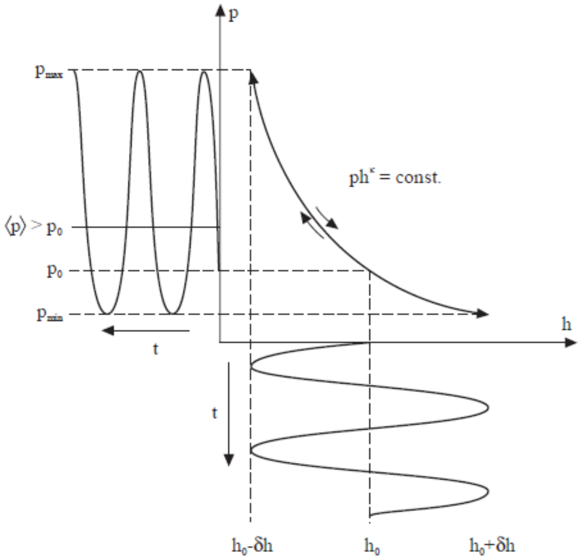


Figure 2: Graph $p(h)$. Under graph oscillations of height h are shown which are responsible for presure oscillations. Harmonic oscillation of h creates non-harmonic oscillation of pressure p. Average pressure of this oscillation exceeds ambient pressure. In air value for κ is 1.4). [2]

Analitical solution (simplified to linear equation using $h_0 << \lambda$; [2]) for pressure inside the gap can be written as

$$p = \frac{1+\kappa}{4} \, \rho_0 c^2 \, \frac{(\delta h)^2}{h_0^2} \tag{3}$$

Pressure is expressed with ratio of specific heats $\kappa = \frac{c_p}{c_V}$, density of a surrounding medium ρ_0, speed of sound in that medium c, amplitude of oscillations of vertical size of the gap and its equilibrium position. Experimentally it was shown that force, calculated from this expression, is overestimated for about 25% ([2]).

Distinguishing between force in near-field and standing wave levitation system is due to different boundary conditions. In general force acting on an object is expressed as

$$\vec{F} = \int p\vec{n}dS. \tag{4}$$

To express acoustic force in case of near-field levitation configuration, for pressure p expression (3) is to be taken. Since the fact that except ratio between amplitude of oscillations of distance h and equilibrium position, terms in equation (3) describe medium it is expected for force proportionality $F \propto h^{-2}$ to hold. Experimentally this proportionallity can be proven by determining force dependence of a distance where object is found ([1]). Result is shown in Fig. 3.

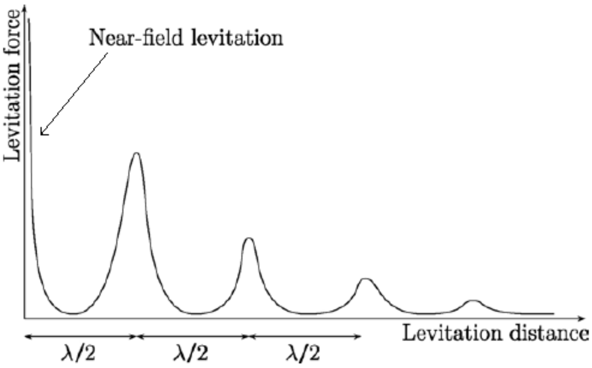


Figure 3: Graph $F(h)$. In experiment ([2]) lifted object was aluminium plate at frequency 19 kHz. Distance h was decreasing and when it reached 0.5 μm amplitude of levitating force was observed to increase. This amplitude, write before contact of object with sound radiator, was measured to be 100 N. Amplitude of force at a distance of $\frac{\lambda}{2}$ (first additional peak) was 1 N. [1]

From graph $F(h)$ we can see additional peaks of force at intervals of distances of half wavelength of sound. This means that object can also be levitated at the distances corresponding to half wavelength of sound. At this condition, between radiator and object standing wave is created. Standing wave holds object at certain distance because of constant transfer of momentum on it. As also can be seen in Fig. 3 additional peaks present forces with much smaller amplitudes than in region very close to sound radiator. In fact in region $h \to 0$ amplitude of force is not restricted showing us that there is no limit of how much mass we can lift using near-field levitation. Providing distance between radiator and planar object is small enough.

With this kind of setup near-film levitation is in some points similar to standing wave limitation (section 3). Between sound source and object at certain distances standing wave is created. However it is still the object that acts as a reflector and levitation is not restricted to object with size smaller than wavelength.

3 Standing wave levitation

3.1 Standing wave levitation

This configuration can be used to levitate objects (particles) with an effective diameter less than the wavelength of sound. In this sheme ([1], [2]) of layout as before is a sound source and above a solid reflector is mounted which usually has concave shape to help focus acoustic waves. Waves are reflected from reflector and interference emerges. As a result in space between radiator and reflector a standing wave is created with so called nodes and anti-nodes (troughs and crests).

Levitating force can be considered as consequence of acoustic radiation pressure. Acoustic radiation pressure is difference between (average) pressure at sphere‘s surface p and hydrostatic pressure p_0 that would have exist if fluid is at rest. For analitic description we can use a model which assumes enough small, incompressible and rigid sphere levitating in presence of acoustic standing wave (King‘s approach; model which was used to derive first analitical description; [3], also [1], [2]). For fluid we assume that effect of viscosity can be neglected and that barotropic relation $p = f(\rho)$ holds. Because of our assumptions we can use Euler‘s equation

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} = -\frac{\nabla p}{\rho}. \tag{5}$$

Assuming also that flow of fluid is irrotational we can express vector of velocity with gradient of scalar function Φ (named velocity potential): $\vec{v} = \nabla \Phi$. Of course continuity equation also holds:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{6}$$

which can also be written as

$$\frac{1}{\rho}\frac{d\rho}{dt} = \nabla^2 \Phi. \tag{7}$$

For a medium (like air) in which from barotropic relation follows $\frac{dp}{d\rho} = f\prime(\rho) = const. = c^2$ differential equation for Φ exact to first order leads to wave equation for Φ:

$$\nabla^2 \Phi = \frac{1}{c^2}\frac{\partial^2 \Phi}{\partial t^2}. \tag{8}$$

Equation (5) can be written as

$$\nabla \dot{\Phi} = \nabla \Big(\int \frac{dp}{\rho} \Big) \tag{9}$$

from which follows non-stationary Bernoulli equation ([4])

$$\dot{\Phi} - \int \frac{dp}{\rho} = \frac{v^2}{2}. \tag{10}$$

For further derivation of integral $\int \frac{dp}{\rho}$ we expand barotropic relation into series in terms of factor $s = \frac{\rho - \rho_0}{\rho_0}$:

$$p = f(\rho_0 + s\rho_0) \approx f(\rho_0) + s\rho_0 f\prime(\rho_0) + \frac{1}{2}s^2\rho_0^2 f\prime\prime(\rho_0) + ... \tag{11}$$

From this expansion we can express dp and combine it with expression $\rho^{-1} \approx \rho_0^{-1}(1 - s + s^2 - ...)$. Eliminating factor s and regarding $f(\rho_0) = p_0$, equation for pressure variation in the medium can be expressed:

$$\delta p = p - p_0 = \rho_0 \frac{\partial \Phi}{\partial t} + \frac{\rho_0}{2c^2}\Big(\frac{\partial \Phi}{\partial t}\Big)^2 - \frac{1}{2}\rho_0 v^2. \tag{12}$$

To get solutions for pressure variation we need to calculate velocity potential from wave equation (8). For that we need to take into consideration boundary conditions which of course sharply depend on geometry of the levitated object.

Solution for Φ from (8) will be oscillatory. For small spheres equality $\Phi = |\Phi| \cos kh \cos \omega t$ can be shown (h denotes position of levitated particle in z-direction). From definition of velocity potential and Bernoulli equation (10) it follows that pressure variation will also oscillate along distance between sound radiator and levitated object.

It can be shown that force on enough small levitated particle created in travelling waves is smaller for few orders of magnitude ([3]; $F \propto r_s^6$) than force created in stationary waves. This is why effect of travelling waves can be neglected.

Acoustic force on a small, rigid sphere (model described before) in a standing wave is derived to be ([3])

$$F = 8\pi r_s^2 (kr_s)\, \bar{E} \sin(2kh)\, f\left(\frac{\rho_0}{\rho_s}\right). \tag{13}$$

It is expressed with wave number k, radius of sphere r_s, mean total energy-density of sound in a medium $\bar{E} = \frac{1}{2}\rho_0 k^2 |\Phi|$, density of sphere ρ_s and so called relative density factor f which in case for stationary wave is defined as

$$f\left(\frac{\rho_0}{\rho_s}\right) = \frac{1 + \frac{2}{3}(1 - \frac{\rho_0}{\rho_s})}{2 + \frac{\rho_0}{\rho_s}}. \tag{14}$$

As already mentioned, levitated particle is assumed to be enough small ($kr_s << 1$). As can also be seen on Fig. 4 force on a particle oscillates with two times higher frequency according to oscillation of velocity or pressure. Levitated particle will tend to a region with minimal pressure (pressure nodes). Size of amplitudes of acoustic force in standing wave levitation system is $\sim 10^{-9} N$.

Under microgravity conditions particle will therefore be found exactly in pressure nodes. In terrestrial environment also gravity force is to be taken into account. Gravity tends to drag object downward while acoustic force upward (into nearest pressure node). In this condition particle is found to be slightly below pressure node. This description is not limited only for solid particles but it also holds for liquid particles (droplets) which strongly deform in the presence of levitating force.

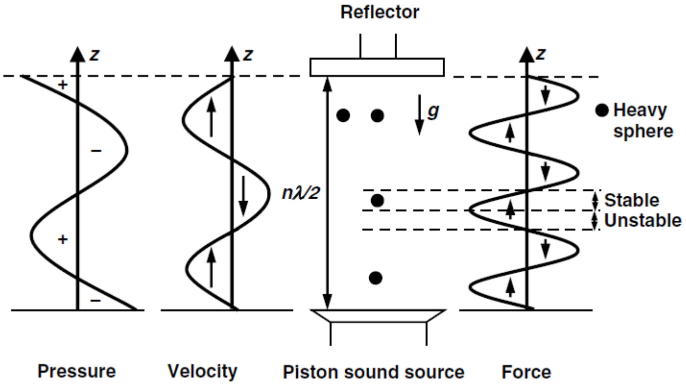


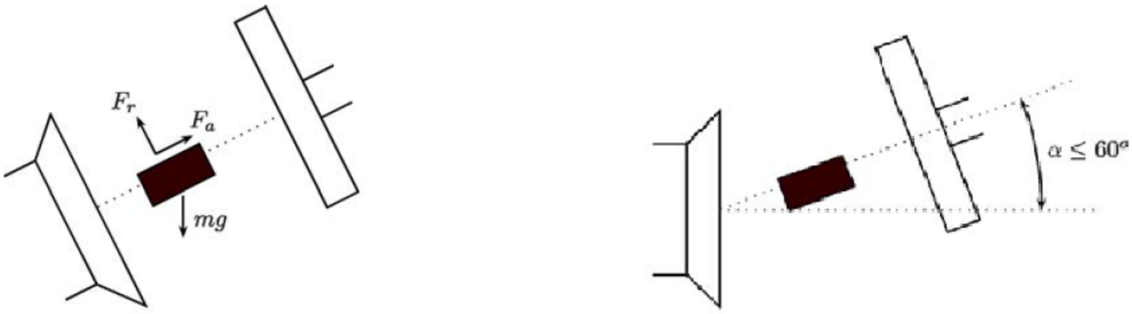
Figure 4: Distribution of sound pressure, acoustic velocity and force on levitated sphere combined with scheme of setup for standing wave levitation. Particle can be stabilized in small interval around pressure node otherwise it is dragged to another nearest pressure node. Distance between radiator and reflector has to be multiple of half wavelength in order to create standing wave. [2]

3.2 Transverse radiation force

So far only one of acoustic forces (also called primary radiation force or axial force) has been mentioned. As figure 4 shows points of pressure nodes are also points of maksimum velocity of flow of medium. Levitated (and stabilized) particle acts as an obstacle so medium flows around particle. Effect of particle on behaviour of flow is restricted to area near particle so velocity of flow around particle decreses away from particle (or z-axis). According to Bernoulli equation (10), this creates aditionall pressure which increases away from z-axis ([1], [5]). This pressure tends to stabilize particle‘s position in transverse direction (x-y plane) similar as primary force stabilizes particle in z-direction. This pressure acts as a force in transverse direction regarding primary force. In case of liquid sample is transverse force also responsible for lateral deformation of it. Amplitude of transverse radiation force is two orders smaller than amplitude of primary radiation force and it has observable effect only once particle reaches pressure nodes, since amplitude of primary force is then zero and transverse force becomes dominant.

Taking into account transverse (also called radial force F_r) acoustic force it is not necessary any more, radiator and reflector to be perpendicular to the z-axis ([5]). If the whole system is tilted for a certain angle (Fig. 5a), the particle is found levitated as long gravity force does not overcome sum of primary and transverse force.

It was also demonstrated that radiator and reflector do not have to be aligned. Setup with angle between axis of radiator and axis of reflector was also tested. Levitation was successfully observed with angles $0 \leq \alpha \leq 60\,^\circ$ (figure 5b).



(a) (b)

Figure 5: (a) Because transverse (radial F_r) force contribute to the acostic force (F_a) levitation does not need to be operated only in an upright position. (b) Levitation can be oparated also when axis of radiator does not coincide with axis of reflector. Their axes can be turned for certain angle. [1]

3.3 Secondary radiation force

Secondary radiation force (also known as Bjerknes forces when acting between gas bubbles or König forces between solid particles) emerges when instead of only one particle we levitate multiple particles in suspension (neglecting other forces like Couloumb interaction). This is interparticle force and its amplitude is also two orders less than primary radiation force. It can be attractive or repulsive and it depends of distance between particles.

Acoustic waves emitted from radiator will scatter on each particle. If two particles in sound field are at certain distance $d >> R_s$ acoustic waves scatter in all regions around particles homogeneously. In region between particles each of them feels scattered wave from other particle into his direction. Scattered wave has momentum which is transferred on particles pushing particle away from its neighbour or with other words creates repulsive force. In case when two particles are close to each other ($d \approx R_s$) majority of acoustic waves will scatter in directions away from particles pushing particles closer to each other. Particles trapped in pressure nodes are very close together because of primary acoustic force. This is why it comes to aggregation of particles once they are positioned in pressure nodes.

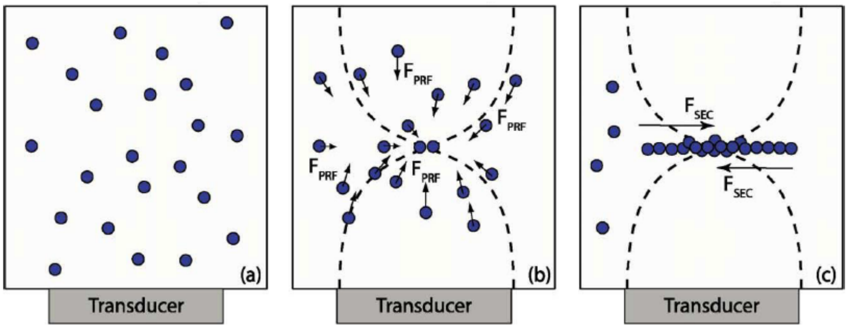


Figure 6: (a) When acoustic field is not present particles in suspension (mixture of fluid and insoluble particles) are free and spreaded across volume of a chamber. (b) In presence of standing wave primary acoustic force (F_{PRF}) drags particles toward pressure nodes. (c) Secondary acoustic force (F_{SEC}) leads to further aggregation of particles. [5]

3.4 Acoustic potential

Another different approach to derive force on small particle in standing wave field is with acoustic potential. Historically (first in [3]), expressions for acoustic forces were first derived with approach used in section 3.1. For easier and faster approach acoustic potential was defined in such way that acoustic force is obtained from

$$\vec{F} = -\nabla U. \tag{15}$$

Expression for acoustic force, like (13), is of course the same, regardless which approach we use.

Acoustic potential is often expressed ([6]) in form

$$U = 2\pi r_s \left[f_1 \frac{\langle p_0^2 \rangle}{3\rho_0 c^2} - f_2 \frac{\rho_0}{2} \langle v_0^2 \rangle \right] \tag{16}$$

with $\langle v_0^2 \rangle$ and $\langle p_0^2 \rangle$ being time-averaged square of velocity and pressure of the acoustic wave, both considered in the point where levitated object is found. f_1 (monopole coefficient) and f_2 (dipole coefficient) are numerical factors given by

$$f_1 = 1 - \frac{\rho_0 c_0^2}{\rho_s c_s^2} \tag{17}$$

and

$$f_2 = \frac{2(\rho_0 - \rho_s)}{2\rho_s + \rho_0} \tag{18}$$

where again index 0 presents sourrandings (medium) and index s particle (sphere). Expression (16) can be presented with maybe more intuitive form

$$U = V_s \left[f_1 \langle E_{pot} \rangle - \frac{3}{2} f_2 \langle E_{kin} \rangle \right] \tag{19}$$

with V_s as volume of a sphere and $\langle E_{pot} \rangle = \frac{1}{2\rho_0 c^2} \langle p_0^2 \rangle$ and $\langle E_{kin} \rangle = \frac{\rho_0}{2} \langle v_0^2 \rangle$ being averaged potential (of compressed medium) and kinetic (due motion of medium) energy density of acoustic wave.

Particle‘s equilibrium points are at $F_i = \frac{\partial U}{\partial x_i} = 0$. Acoustic force according to (15) depends on geometry of a chamber in which experiment is performed. Several results can be found in [6]. With definition of acoustic potential (15) we can see that particle‘s tendency to minimal

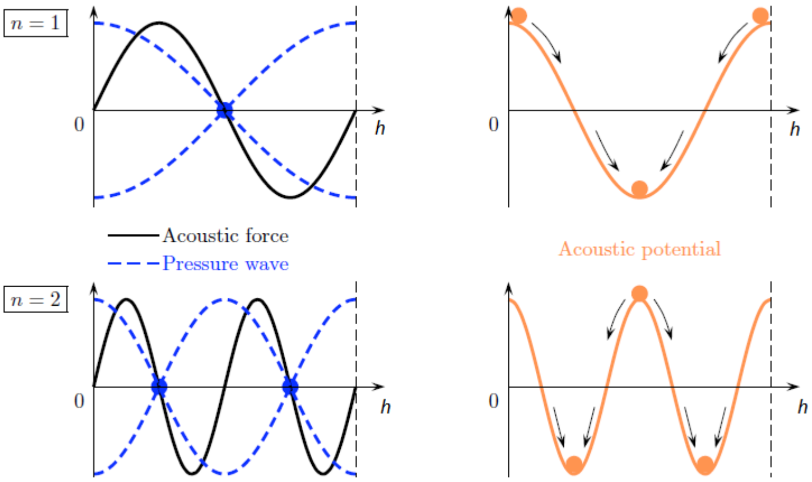


Figure 7: On left is graph of distribution of force and pressure in standing wave according to vertical size of space between radiator and reflector h for one and two nodes ($n = 1, 2$). On right side is corresponding acoustic potencial. Equilibrium points for particle levitation is in points where acoustic potential reaches minimum. [5]

force can be seen as tendency to potential minima. Of course potential and pressure minima coincide (figure 7).

From numerical factors f_1 and f_2 another fact can be noticed ([5], [7]). In case both these factors are positive, minimal value of potential is in points where $\langle v_0^2 \rangle$ is maximal and $\langle p_0^2 \rangle$ is minimal. But with different conditions (when $\rho_0 >> \rho_s$) both of these factors become negative. This means that acoustic potential will be minimal when $\langle v_0^2 \rangle$ is minimal and $\langle p_0^2 \rangle$ is maximal or with different words particle will be found levitating in points of pressure anti-nodes. Example for that are particles of lipid and silicon rubber (in water; [7]). The latter example has positive factor f_2 and negative factor f_1 indicating that this material can be found in both pressure nodes and anti-nodes.

In presence of gravity gravitational term has to be added to expression for acoustic potential (into (16) or (19); [8]): $U = U_{acoustic} + U_{grav}$ where gravitational contribution is defined as

$$U_{grav} = (m_s - m_0)gh \tag{20}$$

Here m_s and m_f stand for mass of particle (sphere) and mass of fluid which is displaced because of presence of particle whereas h again denotes vertical position of particle.

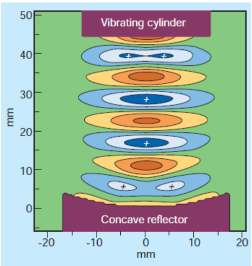


Figure 8: Contour lines of acoustic potential in an experiment. Particle can be trapped in potential wells (denoted by dark blue colour). Because of presence of boudaries, sound source and reflector, acoustic potential is deformed. In experiment sound source and reflector were at the distance 20.3 mm, while frequency was 16.7 kHz. Particles from different material were levitated including balls of tungsten with density 18.9 g/cm^3. [9]

4 Viscous corrections

By now viscosity of medium was neglected. This approximation is justified when there is no presence of rigid boundary in medium and wave attenuation is neglected. Otherwise viscous term $\eta\nabla^2\vec{v}$ has to be added to Euler's equation (5).

In near-field levitation there are two rigid boundaries, bottom surface of radiator and top surface of object ([10]). Because of viscosity acoustic attenuation is emerged, in other words, momentum of acoustic waves is transferred to the medium, resulting in net displacement of it (phenomena known as acoustic streaming) in space between boudaries. This net displacement (stream) creates gradient of streaming velocity and viscous force which acts as holding force (it stabilizes object in horizontal direction). Hence, levitated object is considered stabilized. Experimentally it was noticed that this stream's velocity (streaming velocity) is proportional to amplitude of sound radiator, by increasing amplitude, streaming velocity (and viscous force) also increases. This fact offers application of such levitating system (see section 5).

In standing waves levitation system different corections are considered. Thickness (characteristic dimension) of viscous boundary layer is defined as

$$\delta = \sqrt{\frac{2\eta}{\rho_0\omega}}, \tag{21}$$

expressed with η as coefficient of viscosity and ω frequency of sound. In water at $\omega = 1MHz$ and at room temperature its value is $\delta \approx 0.6\,\mu m$ ([7]). In standing wave levitation effect of viscosity can be neglected as long distances within a few δ are not reached. It can also be neglected for particles for which characteristic dimension exceeds characteristic dimension of viscous boudary layer ($r_s >> \delta$). Since we consider model which assumes particles with $r_s << \delta$ we have to regard viscous corrections.

Viscous corrections can be presented with numerical factors f_1 and f_2 used in section 3.4. Since viscosity does not affect pressure in medium but only velocity of its flow, only factor f_2 has to be redefined into

$$f_2\left(\frac{\rho_0}{\rho_s}, \frac{\delta}{r_s}\right) = f_2(\tilde{\rho}, \tilde{\delta}) = \frac{2(1-\gamma(\tilde{\delta}))(\tilde{\rho}-1)}{2\tilde{\rho}+1-3\gamma(\tilde{\delta}))} \tag{22}$$

with factor $\gamma(\tilde{\delta}) = -\frac{3}{2}(1+i(1+\tilde{\delta}))\tilde{\delta}$ and taking only $Ref_2(\tilde{\rho}, \tilde{\delta})$ in (16). If we consider inviscid fluid with $\delta = 0$ equation is reduced $f_2(\tilde{\rho}, \tilde{\delta} = 0) = f_2(\tilde{\rho})$ to previous definition. Force can than again be derived from (15). Contribution of viscous corrections depend on viscosity of medium, material of lifted particle and its diameter. Relative change in force on particle due viscosity of medium strongly differs, from 1% for polystyrene particles with diameter 5 μm to 25% for pyrex glass particles with diameter 0.5 μm ([11]).

5 Applications of acoustic levitation

A promising application is based on near-field levitation, non-contact transportation ([5]). As already mentioned above, streaming velocity is proportional to amplitude of sound radiator. Let's consider that planar object is wider than sound radiator. Creating asymmetric acoustic streaming above radiator also creates asymmetric stream causing movement of object in direction of higher streaming velocity. By aligning several radiators (stator vibrators) with different amplitude of vibrations, we can move levitated object (Fig. 9).

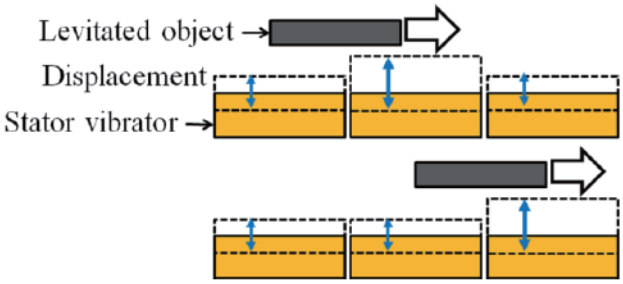


Figure 9: By aligning radiators with different vibrational amplitude, object is moved due difference in viscous force. Object is dragged into direction of higher streaming velocity which is increased by increasing vibrational amplitude. [10]

Standing wave levitation has already been used for several different techniques. Main advantage of this approach is the fact that levitated object is isolated and it can not react with its sorroundings any more. This is very desirable when studying or dealing with chemical reactions especially with the fact that levitated particle is easy reachable and available for handling. In physics ([5]) isolating of sample is desirable when observing phase transitions, process of crystallization (NaCl for instance) or when X-ray structure of proteins, nanoparticles... is in interest. This technique has also been used for example for undercooling liquids below freezenig point and growing ice particles ([9]). Similar use of standing wave levitation is in interesting experiment to isolate droplets of liquid (with typical volume in the range 5 nL to 5 μm corresponding to diameters 0.2 - 2 mm) and observe their evaporation process by illuminating droplet and determing its volume with help of shadows ([12]). With section 3.3 we can also see that we can study aggregation and interactions between particles.

This approach can also be extended for levitation larger and heavier objects ([2]). Idea is based on measurement results in section 2 where, if space between planar object and sound radiator is multiple of half of sound‘s wavelength, standing wave is created.

6 Conclusion

Basic principles of acoustic levitation was first observed in Kundt‘s tube in 1866 when small dust particles moved toward pressure nodes of standing wave. Since then it has found its place as a experimental method in many different subsciences of physics and chemistry, even biology for studying cells. As already mentioned acoustic levitation provides us a tool to isolate particles, samples, cells... Acoustic forces on them are very gentle. It was shown that neither short- neither long-term of exposure of ultrasound does not make any viability losses on cells ([7]). Similar results are shown by levitating small animals (like ladybugs, ants...; [2]). Their vitality was not affected.

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