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# DEPENDENCE OF OSCILLATIONAL INSTABILITIES ON THE AMPLITUDE OF THE ACOUSTIC WAVE IN SINGLE-AXIS LEVITATORS

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## Abstract

It is well known that acoustic waves exert forces on a boundary with which they interact; these forces can be so intense that they can compensate for the weight of small objects up to a few grams. In this way, it is possible to maintain solid or liquid samples levitating in a fluid, avoiding the use of containers, which may be undesirable for certain applications. Moreover, small samples can be manipulated by means of acoustic waves. In this paper, we report a study on the oscillational instabilities that can appear on a levitated solid sphere in single-axis acoustic devices. A theory published on the topic predicts that these instabilities appear when the levitator is driven with a frequency above the resonant frequency of the empty device. The theory also shows that the instabilities can either saturate to a state with constant amplitude, or they can grow without limit until the object falls out of the levitating field or strikes a boundary of the device. These theoretical results are consistent with experiments. According to the theory, the instabilities due to oscillations are produced by a phase difference between the position of the levitated object and the variations of the sound pressure amplitude in the cavity because of the presence of the sample. The theory predicts that the phase difference depends on the speed of the oscillating object. In this paper, we give for the first time experimental evidence that shows the existence of the phase difference, and that it is negatively proportional to the oscillation frequency of the levitated sample. We also present experimental results that show that the oscillational instabilities can be reduced if the amplitude of the acoustic wave is increased; as a result, stable conditions can be obtained where the oscillations of the sphere are highly damped. This dependence of the instabilities on the amplitude of the driving acoustic wave, however, cannot be described with the existing theory.

## 1. INTRODUCTION

Due to the advantages of samples manipulation without the use of tools, and the possibility of container free processing of materials, acoustic levitation has a broad potential of applications. It can be used, for instance, to manipulate dangerous substances, in processes in close spaces to guarantee a controlled environment, and to avoid contamination in the study of samples under high clean requirements. Acoustic levitation has also been used to simulate a microgravity conditions on earth [1].

Among recent applications of acoustic levitation mentioned in the literature are the following ones [2-8]: control evaporation of drops, kinetics of reaction, measurements of thermo-physical properties, super-cooling of levitated drops, studies of critic points in binary liquids, crystals growth, Raman spectroscopy, and formation of ice particles in traps of cold gas.

Axial devices for acoustic levitation have been widely used due to its simplicity. They operate at a single frequency produced by only one transducer and can have a close or an open resonant cavity [1]. A standing sound field is produced in the cavity, and the samples are levitated near the pressure nodes, located along the axis of symmetry.

Several practical problems have to be solved, however, in order to use acoustic levitation in it maximum potential. One of them is the presence of conditions that cause instabilities in these systems. Although materials can be maintained levitating for long times, it is not rare to find situations under which a suspended object spontaneously begins to oscillate or rotate [9-11]. The instabilities can either saturate or develop until the object escapes from the force field or strikes a boundary of the levitation device.

The problem of instabilities in acoustic levitation is complex and has been scarcely treated in the literature. Therefore, a deep investigation is needed to achieve high control on the levitated samples.

In the case of oscillational instabilities in axial devices, where the suspended object moves in the vertical direction around the equilibrium position, the amplitude of the oscillations increases to a finite value (state of saturation). In the worst case, the amplitude continues rising until maintaining the object trapped by the sound field becomes impossible or the conditions inside the device are altered. These kinds of instabilities can appear when the driving frequency is higher than the resonance frequency of the empty cavity of the device.

A first explanation on the causes of the instabilities in single-axis levitators was given by Garret and Barmatz [12]. They proposed a phenomenological description based on two factors: a) the resonance frequency of the cavity depends on the size and position of the object in its interior, and b) a phase difference exists between the speed of the oscillating object and the acoustic force acting on it. Rudnick and Bartmatz [10] proposed a theoretical description based on first physical principles of the causes of the instabilities. They used as a reference the phenomenological explanation suggested previously. Rudnick and Bartmatz took into account the scattering of the acoustic waves produced by a levitated sphere, which was obtained by means of a Green's function. They showed that the variations of the resonance frequency of the cavity, due to the presence and movement of the object, generate a force proportional to the velocity of the object. This force can take the form of a "negative damping" when the driving frequency is higher than the resonance frequency of the empty cavity. In this way, the amplitude of the oscillations tends to increase. Their theory predicts the state of saturation of the instability and the case in which the amplitude of the oscillation grows up without limit. However, it is not possible to predict the dependence of the instabilities on the sound pressure level in the resonant cavity.

The general objective of the work described in this paper has been to investigate the oscillational instabilities that can occur in axial devices for acoustic levitation. The principal purpose was to confirm experimentally the main cause for the instabilities, i.e., the phase difference between the sound pressure amplitude and the position of an oscillating object. In addition, since experimental evidence has shown that the existing theory is incomplete, the purpose has been also to explore experimentally the conditions for the appearance of the instabilities,

## 2. THEORY

Rudnick and Barmatz developed a theoretical description for the oscillational instabilities of a levitated sphere [10]. The equation of motion that they obtained has the following form:

$$m\frac{d^2z}{dt^2}+\left[\xi-\chi(z(t))\right]\frac{dz}{dt}+f_0(z(t))-mg=0\ , \qquad (1)$$

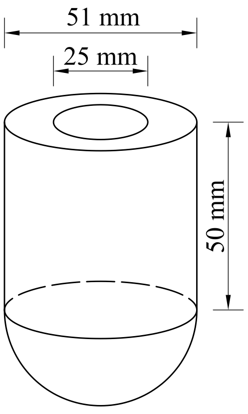
where $m$ is the mass of the sphere, $z(t)$ is the position of the object along the vertical direction in the levitation device, $f_0(z(t))$ is the acoustic levitation force, $\xi$ is the viscosity coefficient, and $\chi(z(t))$ is and acoustic coefficient due to the presence of the object, which is given by [10]:

$$\chi(z(t))=4\frac{P_M^2V}{\rho_0c^2\omega_0(z)}\left(\frac{d\omega_0(z)}{dz}\right)^2\gamma\frac{\gamma(\omega_0(z)-\omega)}{\left[\gamma^2+(\omega_0(z)-\omega)\right]^2}\ . \qquad (2)$$

Here $P_M$ is the amplitude of the acoustic field, $V$ is the volume of the close cavity, $\rho_0$ is the mean density of the medium, $\omega$ is the driving angular frequency, $\omega_0(z)$ is the resonance frequency of the cavity as a function of the vertical position and the size of the object, and $\gamma$ is the quality factor of the empty cavity divided by the resonance frequency without the object. This acoustic coefficient can have negative values, which produces a force on the levitated sphere that increases the amplitude of its oscillations. In this case, the effect is similar to a "negative damping".

## 3. EXPERIMENT

We used for the experiments a polystyrene sphere with a radius of 4 mm and a mass of 7.5 mg inside a cavity formed by a cylindrical section and a semi-sphere. A diagram of the cavity and a picture with the sphere in its interior can be seen in Figure 1.



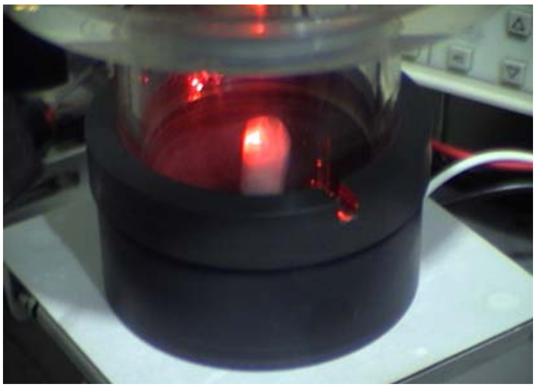



Figure 1. Diagram (left) and a picture (right) of the cavity used for the experiments. The latter shows the moment at which the oscillating sphere blocks a laser beam implemented to detect the time when the sphere was at the top of its movement.

The semi-sphere in the lower part of the cavity gave the possibility of generating a radial force on the levitated object to keep it along the axis of the cavity, away from the lateral boundaries. A driver for a horn loudspeaker, with an opening of 2.5 cm in diameter, was used to generate the sound field.

The experimental system is illustrated in Figure 2. The sound field inside the small chamber was measured with a probe microphone located close to the upper surface, which was connected to a measuring amplifier. In order to determine the frequency response of the empty cavity, measurements were carried out with the tip of a probe microphone at the lower point of the cavity, which coincides with the position of the pressure antinode. It should be mentioned that the sound field inside the cavity, in particular the resonance frequency, was very sensitive to changes in the temperature; therefore, it was monitored during the experiments by using a thermocouple. The measured resonance frequency of the empty cavity was 5026 Hz at a temperature of 26 ºC.

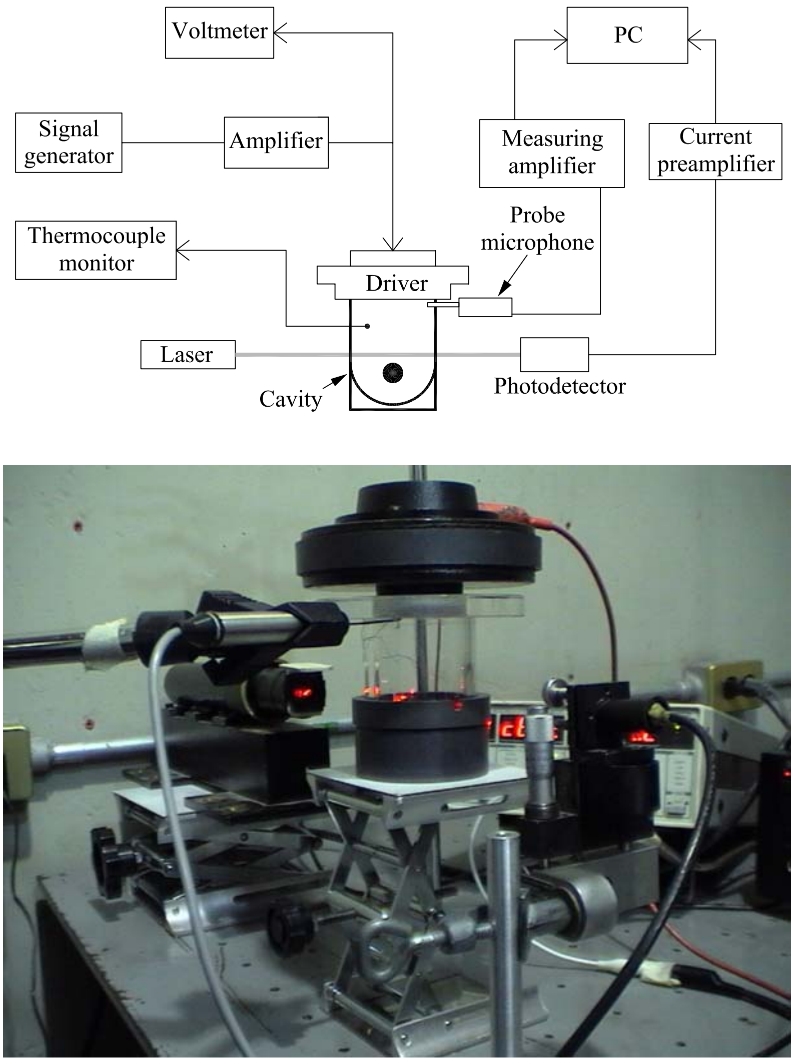



Figure 2. Diagram of the experimental setup, and a picture showing the cavity with the driver, the probe microphone, the laser and the photo detector.

To determine the time when the oscillating sphere was at the upper position of its movement, a laser beam and a photo-detector connected to a current preamplifier were utilized. When the sphere blocked the laser beam, a negative pulse was obtained from the current preamplifier. The time at which the sphere was at its upper position was considered as the middle of the width of the pulse. The output signal from the current preamplifier and the signal from the measuring amplifier were acquired into a PC with a sampling frequency of 42.1 kHz, where the phase difference between the sound pressure and the position of the object was determined.

## 4. RESULTS AND DISCUSION

### 4.1 Phase Difference

When a sound field with a single frequency exists inside the cavity of an axial levitator, the amplitude of the sound pressure depends on the position of the sphere along the axis [10]. The theory developed by Rudnick and Barmatz, predicts a phase difference between the maximum sound pressure amplitude and the position of the sphere in the cavity; the phase difference increases with the speed of the oscillations. However, no experimental evidence was given to confirm this theoretical prediction; it was the purpose of this part of the experiments to corroborate the predictions of the theory.

As mentioned before, the amplitude of the sound pressure, when the levitated sphere was oscillating, changed periodically with the same frequency as that corresponding to the oscillations of the sphere. We compared the time value of the maximum of the periodically changing sound pressure amplitude, with the time at which the sphere was at the upper position of its oscillations. The driving frequency and the amplitude of the voltage applied to the driver were changed to vary the frequency of the sphere oscillations. The graph of the results is shown in Figure 3. Clearly, the phase difference between the maximum of the sound pressure amplitude and the position of the oscillating sphere depends linearly on the oscillating frequency of the sphere. The experimental data fit quite well to a straight line, which has a slope of -0.87 deg/s; the ordinate at the origin was -0.07. During the experiments, we observed that the phase difference depends also on the amplitude of the oscillations of the sphere. Therefore, we tried to keep the same amplitude for different measurements by adjusting the driving frequency and the voltage applied to the driver. The deviations of the experimental results from the fitted straight line were probably caused mainly by the different values of the amplitude of the oscillation of the sphere.

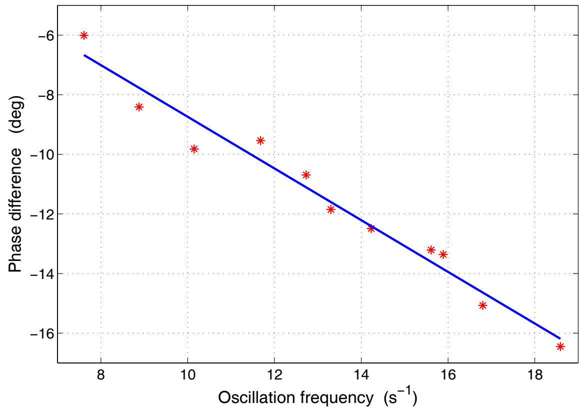


Figure 3: Phase difference between the sound pressure amplitude and the position of a sphere oscillating inside the levitation device.

### 4.2 Zones of Stable Levitation and Zones of Instabilities

Three zones were identified corresponding to different behaviours of the system. At frequencies between 4990 and 5019 Hz, it was possible to levitate the sphere, providing the sound pressure level was sufficiently high, always under stable conditions. The minimum sound pressure amplitude needed to levitate the sphere for any frequency at that interval corresponded to approximately 1000 Pa at the antinode, at the lower point of the resonant cavity. In this case, any oscillation of the sphere that would appear, for instance when this object was just levitated, were rapidly damped. At frequencies higher than 5020 Hz, vertical oscillations of the sphere with constant amplitude were observed. Depending on the value of the sound pressure amplitude, three different cases emerged for a given driving frequency above 5020 Hz (Figure 4). If the sound pressure level was relatively low, the amplitude of the oscillations increased until the sphere hit the boundaries of the cavity (instability region). When we increased the sound pressure level, the movement of the sphere evolved to a state with constant amplitude (second region). By further increasing the sound pressure, the amplitude of the oscillations of the sphere became smaller and the frequency of the oscillations got higher. For larger values of the sound pressure, stable conditions were obtained and the oscillations of the sphere were rapidly damped until it was levitated at rest without visible oscillations.

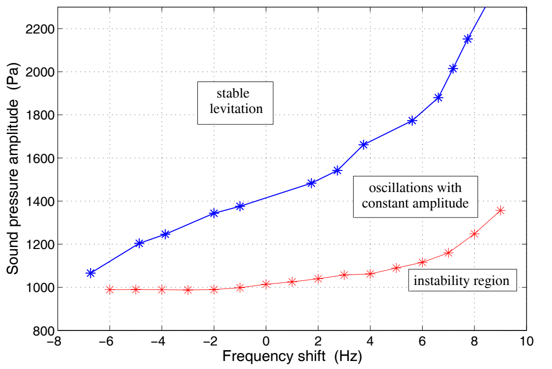



Figure 4. Experimental results showing three regions of different states for the levitated sphere. At frequencies lower than 5019 Hz, only stable conditions were observed. The sound pressure values were measured without the sphere, and the frequency shift indicates the difference between the driving frequency with respect to the resonance frequency for the empty cavity (5026 Hz).

A red mark in Figure 4 corresponds to the highest sound pressure, at a given frequency, where instabilities were observed. To obtain the value of the sound pressure, firstly, the sphere was set into oscillations with constant amplitude; then the sound pressure was slowly reduced, increasing the amplitude of the oscillations of the sphere, until it hit a boundary. Each of the values corresponding to the blue marks was obtained by slowly increasing the sound pressure amplitude, while the sphere was oscillating with constant amplitude, until it came to rest. In this case, the temperature inside the cavity varied slightly during the measurements, and a correction on the frequency shift was applied by calculating the corresponding resonance frequency for the empty cavity at the temperature registered during the experiment.

According to the results of Figure 3, one can conclude that stable conditions of levitation are achieved by increasing the sound pressure in the cavity, which cannot be predicted with the existing theory.

## 6. CONCLUSIONS

According to the results reported here, we have confirmed for the first time to our knowledge that a phase difference exists between the periodic variation of the sound pressure amplitude and the position of an oscillating sphere. This is believed to be the main reason of the oscillational instabilities in single-axis acoustic levitators. We obtained that the phase difference is proportional to the oscillation frequency of a suspended sphere. Moreover, we have shown that the oscillational instabilities can be controlled by increasing the sound pressure level inside the cavity of the acoustic levitator, which cannot be explained by the existing theory. By increasing the sound pressure level in the levitation chamber, both, the amplitude and the frequency of the oscillations change; they vary in opposite senses, the amplitude lowers and the frequency rises. Future work will aim to simulate the behaviour of a levitated sphere in a single-axis levitator to improve the understanding of the physical causes of the oscillational instabilities.

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