Micromanipulation of Small Particles with Ultrasound

Doctoral exam
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OVERVIEW

- Particles are manipulated by acoustical forces.
- These forces appear in a sound field that is excited between a vibrating glass plate and a rigid surface.

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I INTRODUCTION

I.1 MOTIVATION

- Aim: manipulation of small particles with ultrasound.
- Reasons to consider the manipulation with ultrasound:
  - Handling of small particles with solid instruments is problematic (sticking, damage).
  - Ultrasonic manipulation is a complementary method to existing techniques of non-contact manipulation (e.g. optical tweezers, Dielectrophoresis [DEP]).

I.2 SPECIFICATION FOR THE ULTRASONIC MICROMANIPULATION

- Contactless (not contact to solid bodies) manipulation,
- Single or multiple particles (mechanical parts, biological cells, etc.),
- Size of the particles lies between 10μm and 100μm.

I.3 HISTORICAL DEVELOPMENT

<table>
<thead>
<tr>
<th>Event</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>First description</td>
<td>1886</td>
</tr>
<tr>
<td>Calculation of the force</td>
<td>1934</td>
</tr>
<tr>
<td>First idea of an application</td>
<td>1940</td>
</tr>
<tr>
<td>Calculation of the force</td>
<td>1955</td>
</tr>
<tr>
<td>Calculation of the force</td>
<td>1961</td>
</tr>
<tr>
<td>Acoustic filters</td>
<td>1980-...</td>
</tr>
<tr>
<td>Acoustic manipulation</td>
<td>1990-...</td>
</tr>
<tr>
<td>Acoustic micromanipulation</td>
<td>2000-...</td>
</tr>
</tbody>
</table>

2) King L. V.; On the Acoustic Radiation Pressure on Spheres; Proc. a. t. R. Soc. of London. Ser A, Math. and phys. sc. 1934; Vol. 147.
3) US 2,215,484; St Clair H. W.; Sonic Flocculator and Method of Flocculating Smoke or the Like (1940-09-24).
5) Gorkov L. P .; Forces Acting on a Small Particle in an Acoustic Field within an Ideal Fluid; Doklady Akademii Nauk Sssr 1961; Vol. 140, Iss. 1, pp 88-.
II SOUND FIELD IN THE FLUID LAYER

II.1 HOW CAN PARTICLES BE MANIPULATED BY A SOUND FIELD?

- When a particle is placed in a sound field, it experiences a force.

- The magnitude of the force depends on the frequency, the radius of the particle and the material parameters.

III SOUND FIELD IN THE FLUID GAP

- The sound field is emitted by a vibrating surface with the displacement $u_{Sf}$ and reflected by a rigid surface.

- The sound field is modelled as a superposition of four plane waves ($\phi_1, \phi_2, \phi_3,$ and $\phi_4$).

- The resulting velocity potential is given by

$$\phi_F = \sum_{m=1}^{4} \phi_m = i \frac{\Phi_F}{\sin(hk_{Sf})} \cos(xk_{Sf}) \cos((h + y)k_{Sf}) e^{i\omega t}$$

$x, y$ ... spatial coordinates
$k_{Sf}, k_{Sf}$ ... wave numbers
$u_{Sf}$ ... displacement amplitude
$\phi$ ... velocity potential
$\omega$ ... angular frequency
$t$ ... time
$h$ ... height of the fluid gap
$\lambda_{Sf}$ ... wavelength of the surface
III.1 THE FORCE FIELD IN THE FLUID GAP

III.1.1 PRIMARY FORCES

- The force field acting on the particles in the fluid $\langle \vec{F} \rangle$ can be calculated from the force potential $\langle U \rangle$:

$$\langle \vec{F} \rangle = -\nabla \langle U \rangle,$$

with

$$\langle U \rangle = 2\pi r_s \rho_f \left( \frac{1}{3} \frac{\langle p^2 \rangle}{\rho_f c_f^2} f_1 - \frac{\langle q^2 \rangle}{2} f_2 \right).$$

1) L. P. Gorkov, Forces Acting on a Small Particle in an Acoustic Field within an Ideal Fluid, Doklady Akademii Nauk SSSR 140 (1961)

Two-dimensional case
- The particles are concentrated at the minima of the force potential.
- It depends on the material combination where these minima lie.
- With a quasi one-dimensional plate wave the sound field is two-dimensional and the particles will be arranged in lines.
• Three-dimensional case
  
  – When the plate wave propagates in two perpendicular directions, the sound field is three-dimensional and it is possible to concentrate single particles in points.

  – A large quantity of particles will be arranged in ellipse shaped areas (according to the isolines of potential of forces).

IV DISPERSION RELATION OF A PLATE WITH FLUID LOADING

IV.1 CHARACTERISTIC EQUATION

• The plate has a thickness of \( d \).

• The fluid is on one side, at \( y = -h \), in contact with a rigid surface and on the other side, at \( y = 0 \), in contact with the vibrating plate.

• For the calculation of the dispersion relation of the plate/fluid combination the displacement potentials in the plate are assumed to be

\[
\begin{align*}
\theta_p &= [\Theta, \cosh qy + \Theta, \sinh qy] e^{i(x - z \phi_p)} \\
\psi_p &= [\Psi, \cosh qy + \Psi, \sinh qy] e^{i(x - z \phi_p)}
\end{align*}
\]

\[
\theta_p = i \frac{\Theta_p}{\sin(hk_{fy})} \cos((h + y)k_{fy}) e^{imu}
\]
• The solution of this system of equation leads to the characteristic equation of the plate/fluid combination

\[
0 = \left[ 16 k_s^2 q^2 s^2 + (k_s + s)^4 - 4q s \left( \tanh \frac{d}{2} s \coth q + \tanh \frac{d}{2} q \coth s \right) k_s (k_s + s)^2 \right] + \\
\left\{ \frac{\rho_s}{\rho_f k_{iy}} \left( (k_s + s)^2 \coth dq - 4q sk_s \coth ds \right) k_s (k_s + s)^2 \cos hk_{iy} \right\}
\]

- wave number in the plate,
- wave numbers corresponding to the longitudinal and transversal waves,
- 
\[
q = \sqrt{k_s^2 - k_i^2}, s = \sqrt{k_s^2 - k_t^2}.
\]

• The first term (blue, in square brackets) is the product of the characteristic equations of the symmetrical and antisymmetrical mode of a free plate.

• The symmetrical and antisymmetrical mode are coupled by the second term of the equation (red, in curly brackets).

IV.2 TWO CASES OF PLATE/FLUID COMBINATIONS

IV.2.1 DOMINATING PLATE (EXAMPLE: 1 mm GLASS PLATE, 0.1 mm WATER LAYER)

- Fluid layer is thin with respect to the vertical wave length in the fluid \( h k_{iy} \ll 1 \), the coupling term has a constant influence on the plate dispersion.

- There is no wave propagation below the speed of sound in the fluid.
IV.2.2 COUPLING OF FLUID AND PLATE (EXAMPLE: 1mm GLASS PLATE, 1mm WATER LAYER)

- The fluid layer is so thick that \(\cos(hk_F)\) has many zero points in the regarded frequency range; such a zero point represents resonance in the fluid layer.

- There is decoupling when \(\cos(hk_F) = 0\), as the coupling term vanishes.

IV.2.3 CONCLUSIONS OF THE INVESTIGATION OF THE PLATE/FLUID DISPERSION

- The first antisymmetrical mode fits the requirements best:
  - It has the smallest wave length,
  - It is easy to excite.

- For a rough estimate it is sufficient to calculate the wavelength of the plate without fluid loading, because its influence is not very strong.
V. TECHNICAL SETUP

V.1 DESIGN OF THE DEVICE

• The device consists of a glass plate and transducers, held in a clamp and a fluid and a rigid surface (does not necessarily belong to the setup).
  – The glass plate and the piezo transducers are only held by the tension in the clamp.

For later experiments the glass plate with the piezo transducers are glued without tension into a holder.

• Advantages compared to the old clamp
  – easier to handle,
  – electrodes of the piezo transducer can be insulated,
  – better results in the experiments (straighter lines, better repeatability).
V.2 EXPERIMENTAL SETUP

- The experimental setup is placed on a vibration insulation table;
- It consists of
  - a microscope with camera and monitor,
  - a light source with fiber optic,
  - a vertical translation stage,
  - a positioning system.
VI.1.2 CONCENTRATION HL60-CELLS IN POINTS \( f = 1.2 \text{MHz} \)
(see “Three-dimensional case”)

- Particles can also levitate in the fluid,
  (see “Two-dimensional case”).

  Lifting of particles from the object slide;
  it is possible to lift a particle from the surface,
  the force at the reflecting surface is zero
  but the sphere is \( r_s \) above this surface.
VI.2 DISPLACEMENT OF PARTICLES

- Three possible principles of horizontal displacement were demonstrated experimentally:
  - Displacement of the glass-piezo-unit
  - Changing the excitation frequency and consequently the wavelength
  - Superposition of two standing waves with different amplitude

VI.2.1 DISPLACEMENT OF THE GLASS-PIEZO-UNIT

- At the initial position the sound field is turned on, so that the particles align according to the sound field.
- Then the full glass-piezo-unit is displaced, the particles follow that movement.

Displacement of particle by a small distance (micrometers)

Displacement of particle by a large distance (millimeters)
VI.2.2 Changing the Excitation Frequency

- The wavelength of the plate wave depends on the excitation frequency (see section IV.2.1).
- When the frequency is increased, the wavelength decreases.

VI.2.3 Superposition of Two Standing Waves with Different Amplitudes

- If two standing waves with a fixed phase and varying amplitudes
  \[ u_1 = \xi \sin(\alpha_1 + k_x x) \quad \text{and} \quad u_2 = (1 - \xi) \sin(\alpha_2 + k_x x) \]
  are superimposed \( u_{sp} = \xi \sin(\alpha_1 + xk_x) + (1 - \xi)\sin(\alpha_2 + xk_x) \),
  the resulting wave has the same wavelength and a varying phase.

Displacement of the nodes of the superimposed wave \( u_{sp} \) for \( \xi \in (0, 1) \) \( (\alpha_2 - \alpha_1 = \pi / 2) \)
Experimental Results
Displacement of Particles

- The signal of the amplifier is split by a voltage divider.
- Two opposite piezo transducers are connected to the connectors $e_1$ and $e_2$.
- By turning the switch, the amplitudes of the voltage at the two transducers can be changed discretely.

One-dimensional positioning (polystyrene beads)

VI.2.4 Comparison of the Three Displacement Principles

<table>
<thead>
<tr>
<th>Displacement of the glass-piezo-unit</th>
<th>Changing the excitation frequency</th>
<th>Superposition of two standing waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ easy to implement</td>
<td>+ geometry stays constant</td>
<td>+ geometry stays constant</td>
</tr>
<tr>
<td>+ electronic parameters stay constant</td>
<td>+ frequency has to be changed</td>
<td>+ electronic parameter stay constant</td>
</tr>
<tr>
<td>- external positioning unit necessary</td>
<td>- displacement is not continuously</td>
<td>- low displacement amplitudes</td>
</tr>
<tr>
<td>- might cause fluid flow</td>
<td></td>
<td>- suitable for small displacement ranges for systems with high accuracy demands</td>
</tr>
<tr>
<td>- suitable for large and small displacement ranges for systems where the glass-piezo-unit can be displaced</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
VII CONCLUSIONS

• Introduction of a method for contactless positioning of small particles.
  – Theoretical derivation of the sound field in a fluid gap which is excited by surface wave.
  – Theoretical derivation of the dispersion relation of plate with fluid loading on one side.

• Introduction of a method and device for contactless positioning and displacement.
  – The device can be placed opposite any plane surface to position particles on it.
  – Possible application are in the field of micro-technology (assembling and aligning of components), bio-technology (handling of cells).

• Presentation of experimental results of one- and two-dimensional positioning and displacement.

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