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A New, Simple Electrostatic-acoustic Hybrid Levitator

E. G. Lierke, H. Loeb, and D. Gross
Battelle Institute, Frankfurt, W. Germany

Battelle has developed a hybrid levitator by combining the known single-axis acoustic standing wave levitator with a coaxial DC electric field. The acoustic 20kHz driver serves as the ground electrode for the electric field, while a convex electrode - integrated into the acoustic reflector - provides a slightly convergent electric field. The resulting Coulomb forces on the charged liquid or solid sample support its weight and, together with the acoustic force, center the sample.

Liquid samples with volumes $\lesssim$ 100 micro-liters are deployed from a syringe reservoir into the acoustic pressure node. The sample is charged using a miniature high-voltage power supply ($\lesssim$ 20 kV) connected to the syringe needle. As the electric field - generated by a second miniature power supply - is increased, the acoustic intensity is reduced.

The combination of both fields allows stable levitation of samples larger than either single technique could position on the ground. Decreasing the acoustic intensity reduces acoustic convection and sample deformation.

Neither the electrostatic nor the acoustic field requires sample positioning sensing or active control.

The levitator - now used for static and dynamic fluid physics investigations on the ground - can be easily modified for space operations.

ELECTROSTATIC-ACOUSTIC HYBRID LEVITATOR

CONSIDERED AREAS OF INTEREST (on ground and under micro-g conditions)

- FLUID PHYSICS EXPERIMENTS (STATIC AND DYNAMIC)
- CRYSTAL GROWTH FROM SOLUTION DROPS
- (SINGLE-DROP COMBUSTION)

CONSIDERED SAMPLES AND ENVIRONMENTAL CONDITIONS

- WATER AND OTHER SOLUTION DROPS IN NEAR-AMBIENT ENVIRONMENT

  VOLUME < $100\mu l$

  AIR AT 1 BAR PRESSURE

  TEMPERATURE: $0^\circ - 100^\circ C$

  RELATIVE HUMIDITY: 0 - 100%

FEASIBLE LEVITATORS

- ACOUSTIC LEVITATOR
- ELECTROSTATIC LEVITATOR
- ELECTROSTATIC-ACOUSTIC HYBRID LEVITATOR

ELECTROSTATIC-ACOUSTIC HYBRID LEVITATOR

FEATURES OF A ONE-AXIAL ACOUSTIC STANDING-WAVE LEVITATOR

1) MULTIAXIAL POSITIONING FORCES RESULT FROM GRADIENTS OF ACOUSTIC RADIATION PRESSURE (AXIAL AND RADIAL, BERNOULLI, PRESSURE) IN A RESONANT STANDING WAVE BETWEEN A PISTON RADIATOR AND A FLAT, TAPERED OR CURVED REFLECTOR. (FIG. 1)

2) THE SAMPLE IS STABLY LEVITATED NEAR THE PRESSURE NODE (VELOCITY ANTINODE) TYPICALLY WITH AXIAL DISPLACEMENTS $< \lambda/8$ AND RADIAL DISPLACEMENTS $< \lambda/4$.

3) AXIAL FORCES ARE STRONGER THAN RADIAL FORCES (4:1).

4) LEVITATION FORCES DECREASE WITH INCREASING ka $(= \pi \frac{d_s}{\lambda})$ AND DIMINISH AT ka > 2.2. (FIG. 2)

5) THE SMALLEST OPTIMAL SOUND PRESSURE LEVEL (SPL) FOR A GIVEN SAMPLE DIAMETER IS REQUIRED AT ka $= \pi/3$ (DIAMETER, $d_s = \lambda/3$).

6) ACOUSTIC LEVITATION FORCES ARE COMBINED WITH CONVECTION CURRENTS IN THE SURROUNDING GAS. (FIG. 3)

7) THESE CONVECTION CURRENTS LEAD TO ENHANCED MASS AND HEAT FLOWS WHICH ARE REPRESENTED BY EFFECTIVE REYNOLDS, SHERWOOD, OR NUSSELT NUMBERS.

8) THE OBLATE DEFORMATION OF ACOUSTICALLY LEVITATED DROPS IN 1-G IS CONSIDERABLY LARGER THAN THE PROLATE DEFORMATIONS IN ELECTROSTATIC LEVITATORS. (FIG. 4)

MAIN EQUATIONS AND PARAMETERS OF THE ACOUSTIC LEVITATOR

AXIAL FORCE:

$$F = \frac{5}{6}\pi \rho_0 \tilde{v}_{max}^2 k a^3 f_1(2ka)\cdot\sin(2k\Delta z) = \frac{4}{3}\pi a^3 \rho_s g_0$$

$k = \frac{\omega}{c_0} = \frac{2\pi}{\lambda}$ $\qquad$ $a = d_s/2$ (d_s is the sample diameter)

$\rho_0 c_0^2 = p_0 \gamma$ $\qquad$ ρ_s = sample density

$g_0 = 9.81\ m/s^2$ (sea-level grav. accel.)

$\tilde{v}_{max}$ - antinode velocity amplitude

$\tilde{p}_{max}$ - antinode acoustic pressure amplitude

$M_{ac} = \frac{\tilde{v}_{max}}{c_0}$ - acoustic Mach number

$\phi_s = \sin^{-1}(2k\Delta z)$ - levitation safety factor

Δz - displacement of sample from pressure node

$$f_1(2ka) = \frac{3}{(2ka)^3}\left\{\frac{\sin(2ka)}{2ka} - \cos(2ka)\right\} = \frac{1.31}{2ka} f_2(2ka)$$

$$M_{ac}^2 = \frac{8}{5}\frac{\rho_s g_0}{P_0 \gamma k}\frac{\phi_s}{f_1(2ka)} = 1.22\frac{\rho_s g_0 d_s}{P_0 \gamma}\frac{\phi_s}{f_2(2ka)}$$

ELECTROSTATIC-ACOUSTIC HYBRID LEVITATOR

MAIN EQUATIONS AND PARAMETERS OF THE ACOUSTIC LEVITATOR

CONVECTION FLOW VELOCITY ARROUND SAMPLE:

$$\hat{V} \simeq \frac{\tilde{v}_{max}^{2}}{\omega a} = \frac{c}{ka} M_{ac}^{2}$$

REYNOLDS NUMBER FOR ACOUSTIC CONVECTION:

$$Re = \frac{d_s \hat{V}}{\nu} = \frac{2 c_0}{\nu k} M_{ac}^{2} \qquad (\nu : \text{kinematic viscosity})$$

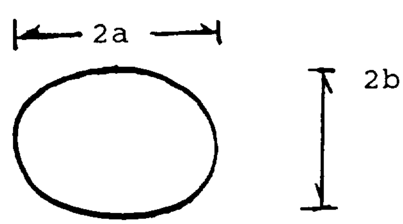
SOUND PRESSURE LEVEL:

$$SPL\ [dB] = 10 \log \frac{\tilde{p}_{max}^{2}}{2\, P^{*2}} \simeq 194 + 10 \log M_{ac}^{2}$$

BOND NUMBER:

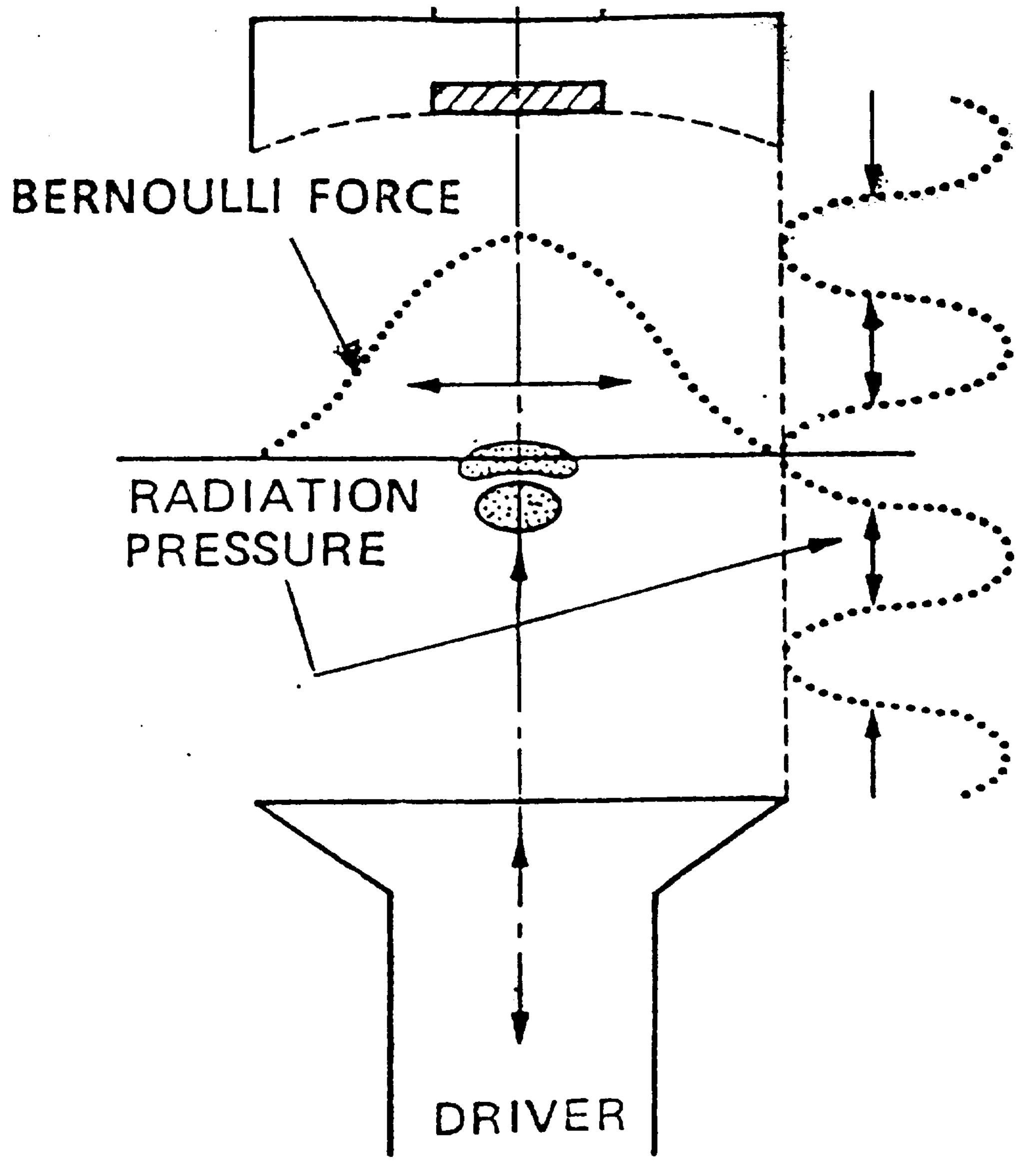
$$B = \frac{\rho_s}{\sigma_s} \frac{d_s^{2}}{4} g \qquad (\sigma_s : \text{surface tension})$$

ASPECT RATIO: a/b



Characteristic parameters for terrestrial levitation of water drops ambient air at 21 kHz

d [mm]:	2	3	4	5	6
$M_{ac} \cdot 10^{2}$	1.93	2.0	2.12	2.29	2.53
$\hat{V}$ [cm/s]	32	23	19.4	18	18
Re	46	49.6	56	65.4	78.4
SPL [dB]	159.7	160	160.5	161.2	162.1
a/b	1.18	1.36	1.6	1.9	2.1
$f_1(2ka)$	0.94	0.87	0.77	0.66	0.55
$f_2(2ka)$	0.56	0.78	0.93	1.00	0.98
Bo	0.136	0.307	0.545	0.85	1.22



$$p_{rad} = \frac{p^2}{2\varrho c^2} \cdot \sin^2 k_z z \cdot \cos^2 k_r r$$

$$p_{Bern} = - \varrho/2 \cdot v^2 \cos^2 k_z z \cos^2 k_r r$$

Fig. 2: Drop levitation in an one-axial acoustic levitator (schematical)

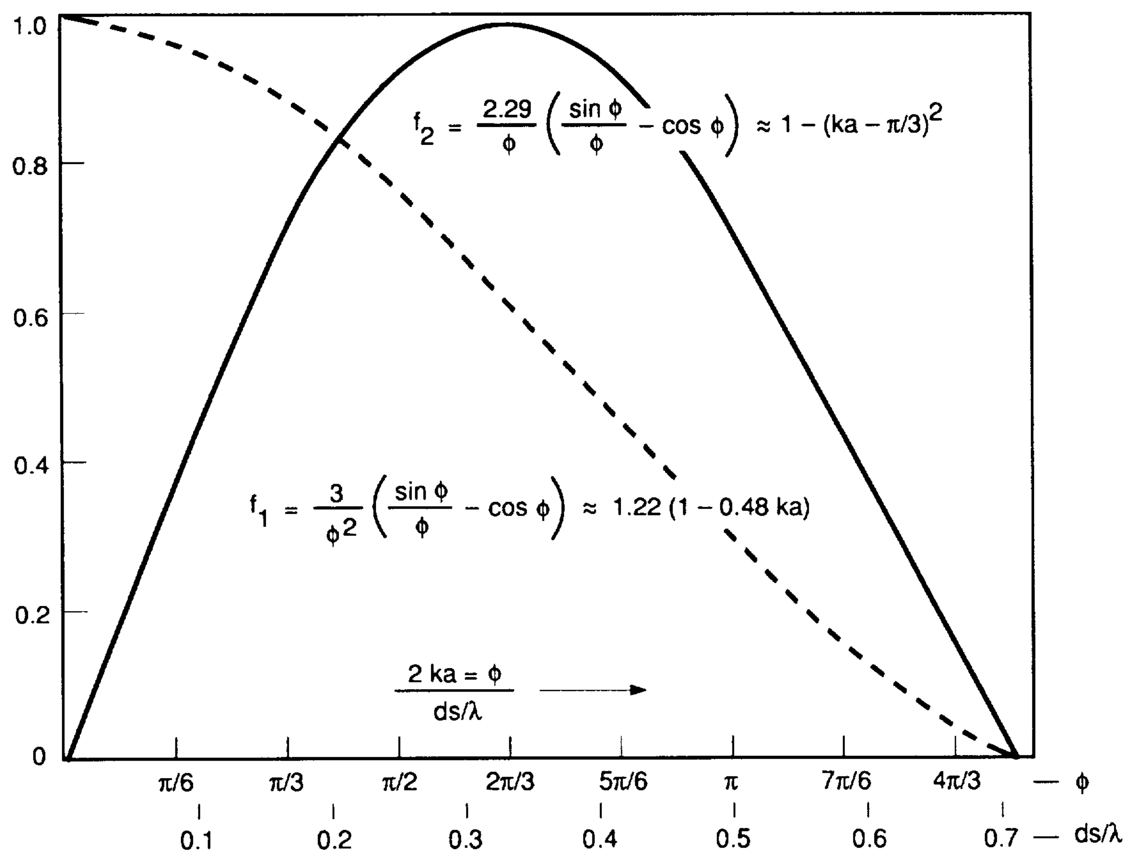
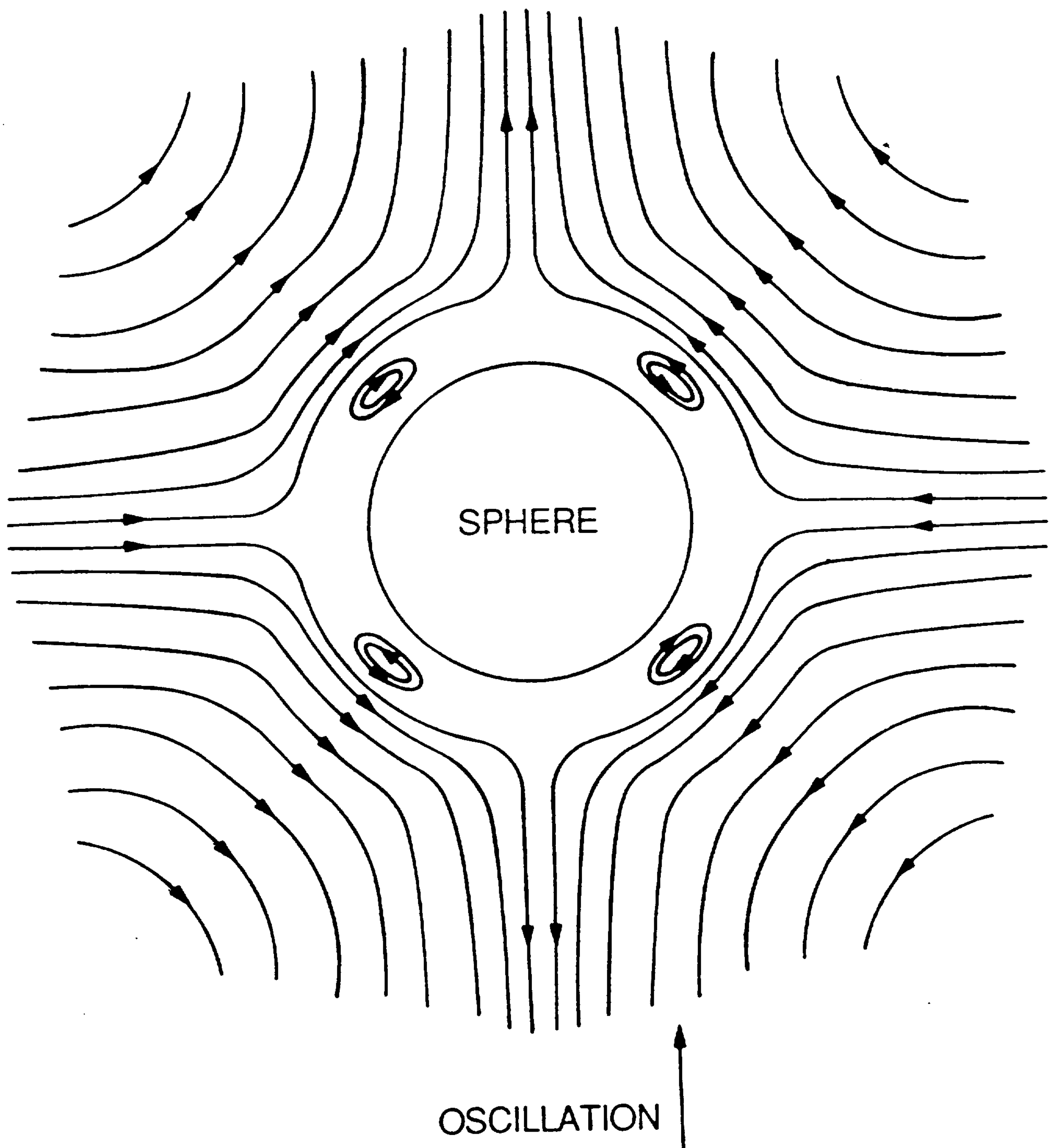
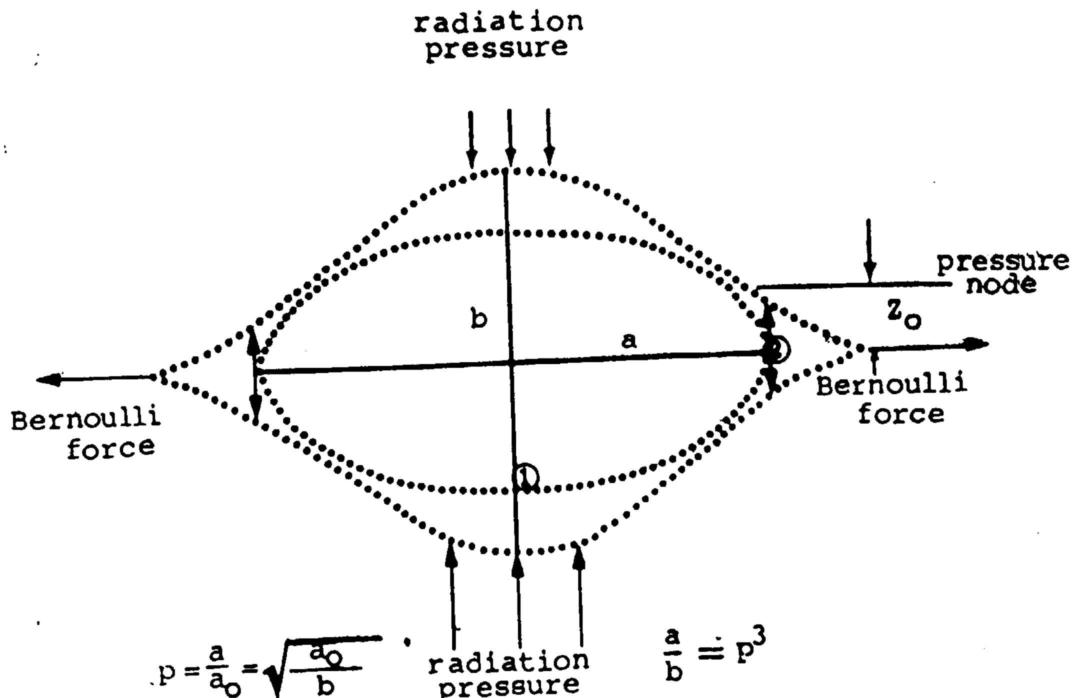

1.0
0.8
0.6
0.4
0.2
0
$f_2 = \frac{2.29}{\phi}\left(\frac{\sin\phi}{\phi} - \cos\phi\right) \approx 1 - (ka - \pi/3)^2$
$f_1 = \frac{3}{\phi^2}\left(\frac{\sin\phi}{\phi} - \cos\phi\right) \approx 1.22\,(1 - 0.48\,ka)$
$\frac{2\,ka = \phi}{ds/\lambda}$
π/6
π/3
π/2
2π/3
5π/6
π
7π/6
4π/3
— φ
0.1
0.2
0.3
0.4
0.5
0.6
0.7 — ds/λ

Figure 2.


SPHERE
OSCILLATION



$$\Phi_s = \frac{F_{ac}}{m_s g_o} \text{ – Safety factor} \quad ; \qquad B_o = \frac{\rho_s}{\sigma_s} a_o^2 g_o \text{ – Bond number}$$

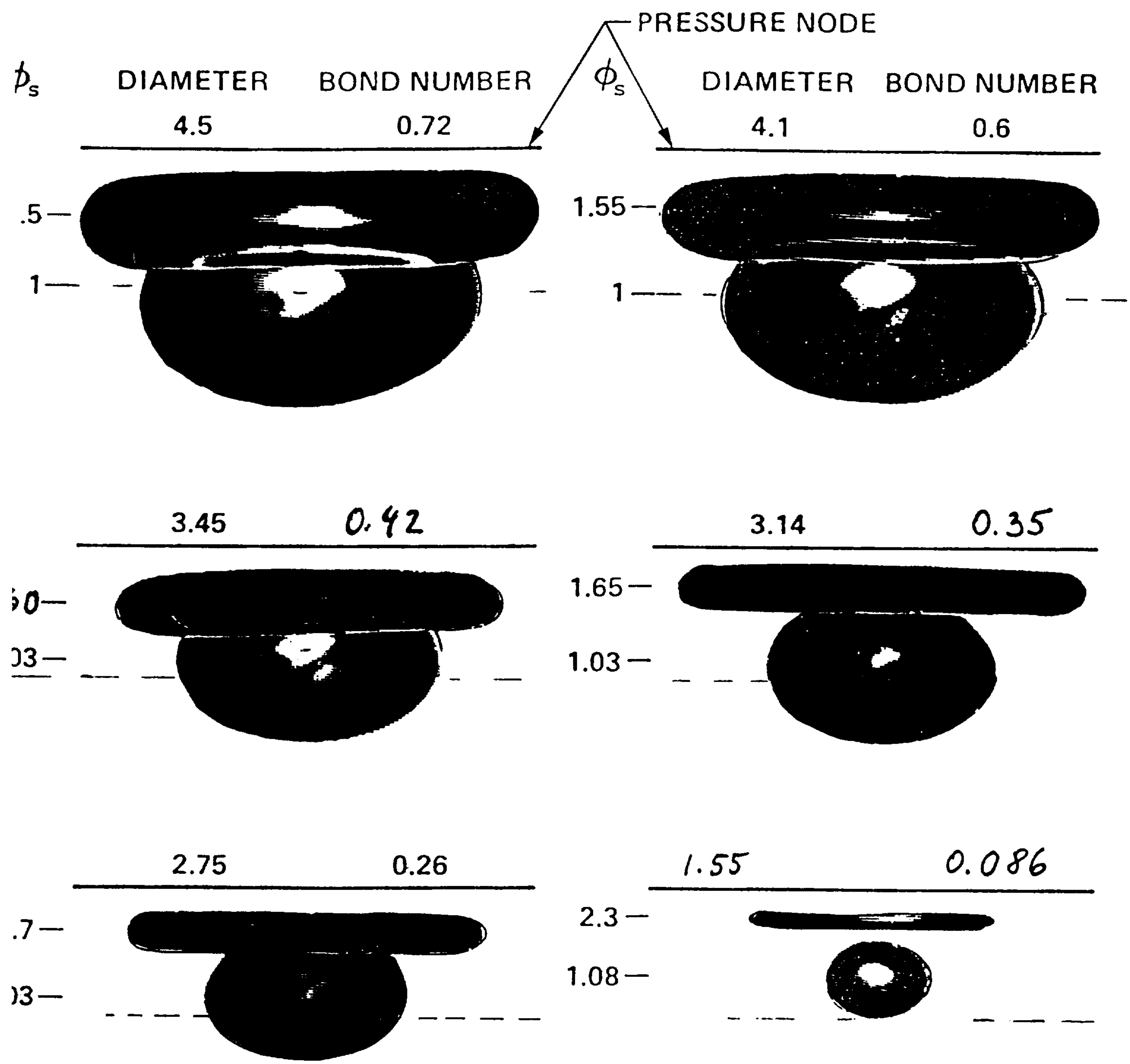


FIGURE 3

YPICAL AXIAL DISPLACEMENT AND DEFORMATION OF WATER DROPS OF DIFFERENT INITIAL RADIUS a_o AT SMALL AND LARGE LEVITATION SAFETY FACTOR Φ_s IN A ONE-AXIAL 20 kHz ACOUSTIC LEVITATOR IN AIR (λ = 17mm)

ELECTROSTATIC-ACOUSTIC HYBRID LEVITATOR

FEATURES OF THE ELECTROSTATIC LEVITATOR

1) AXIAL POSITIONING FORCES RESULT FROM COULOMB FORCES ON A SAMPLE WITH CHARGE, Q, IN A HOMOGENEOUS ELECTRIC FIELD, E (AS KNOWN FROM MILIKAN'S EXPERIMENT). (FIG. 5)

2) THE BALANCE BAETGWEEN SAMPLE WEIGHT AND LEVITATION FORCE IS UNSTABLE AND REQUIRED ACCURATE POSITIONING CONTROL AND VOLTAGE CONTROL WITH AN APPROPRIATE TIME CONSTANT (SERVO-CONTROLLED POWER SUPPLY).

3) SMALL RADIAL FORCES CAN ABE PROVIDED WITH TAPERED OR CURVED ELECTRODES.

4) THE SAMPLE ENVIRONMENT CAN BE ANY GAS OR VACUUM. THERE ARE NO FORCED-CONVECTION CURRENTS.

5) DEPLOYMENT AND EXTRACTION OF A LIQUID SAMPLE ARE MORE DIFFICULT THAN IN ACOUSTIC LEVITATORS.

6) THE PROLATE DEFORMATION OF LIQUID SAMPLES IS SMALL COMPARED TO THEAT RESULTING FROM ACOUSTIC LEVITATION.

7) SAMPLE CHARGE, Q, AND ELECTRIC FIELD, E, MUST BE SLECTED WITH ATTENTION TO THE RAYLEIGH–TAYLOR INSTABILITY LIMITS. (FIG. 6)

ELECTROSTATIC-ACOUSTIC HYBRID LEVITATOR

MAIN EQUATIONS AND PARAMETERS OF THE ELECTROSTATIC LEVITATOR

$$F_{el} = E \cdot Q = \frac{4}{3}\pi a_s^3 \rho_s g$$

$$Q = 4\pi \varepsilon_0 a_s U_2$$

$$E = \frac{U_1}{l}$$

NORMALIZATION (RAYLEIGH-TAYLOR LIMIT)

$$\bar{E} = \frac{U_1}{l}\sqrt{\frac{4\pi a_s \varepsilon_0}{\sigma_s}} \qquad \bar{Q} = \frac{U_2}{a_s}\sqrt{\frac{4\pi \varepsilon_0 a_s}{\sigma_s}}$$

$$\bar{F}_{el} = \frac{F_{el}}{\frac{4}{3}\pi \sigma_s a_s} = \frac{\bar{E}\cdot\bar{Q}}{\frac{4}{3}\pi} = Bo = \frac{\rho_s}{\sigma_s} a_s g$$

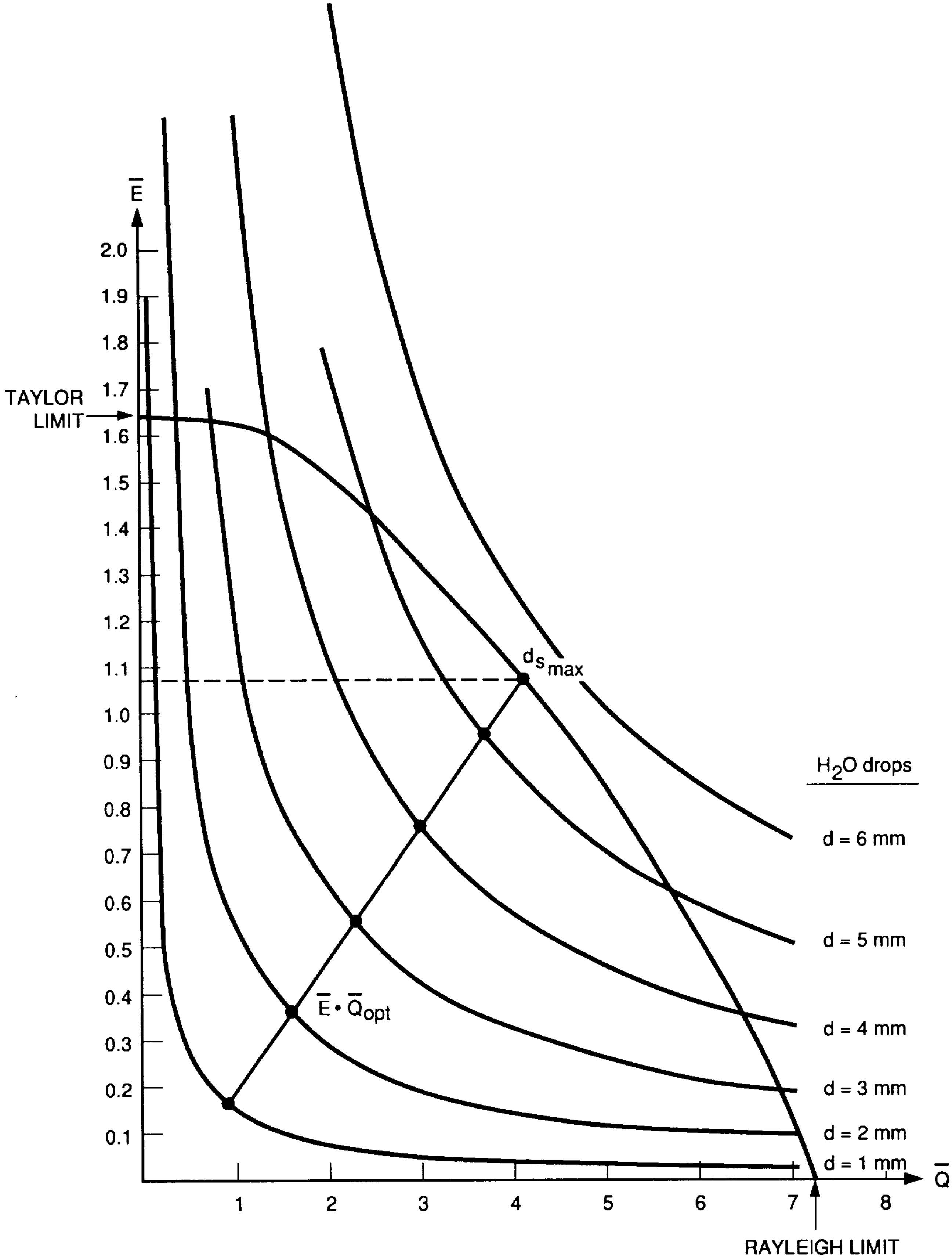
RAYLEIGH-TAYLOR LIMIT FOR VARIOUS BOND NUMBERS

Bo:	0.2	0.4	0.6	0.8	1.0	1.06
Q(min)	0.55	1.05	1.55	2.30	3.45	4.25
Q(max)	6.95	6.65	6.30	5.80	5.00	4.25

$$\bar{Q}_{opt} \simeq 4.2 \qquad \bar{E}_{opt} = Bo$$

$$U_2\,[kV] \simeq 7.5\sqrt{d_s\,[cm]}$$

$$U_1\,[kV] \simeq 39\ d_s\,[cm] \quad \text{for} \quad = 3.2\text{cm}.$$



$\overline{E}$
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
TAYLOR LIMIT
$d_{s_{max}}$
$\overline{E} \cdot \overline{Q}_{opt}$
H_2O drops
d = 6 mm
d = 5 mm
d = 4 mm
d = 3 mm
d = 2 mm
d = 1 mm
1
2
3
4
5
6
7
8
$\overline{Q}$
RAYLEIGH LIMIT

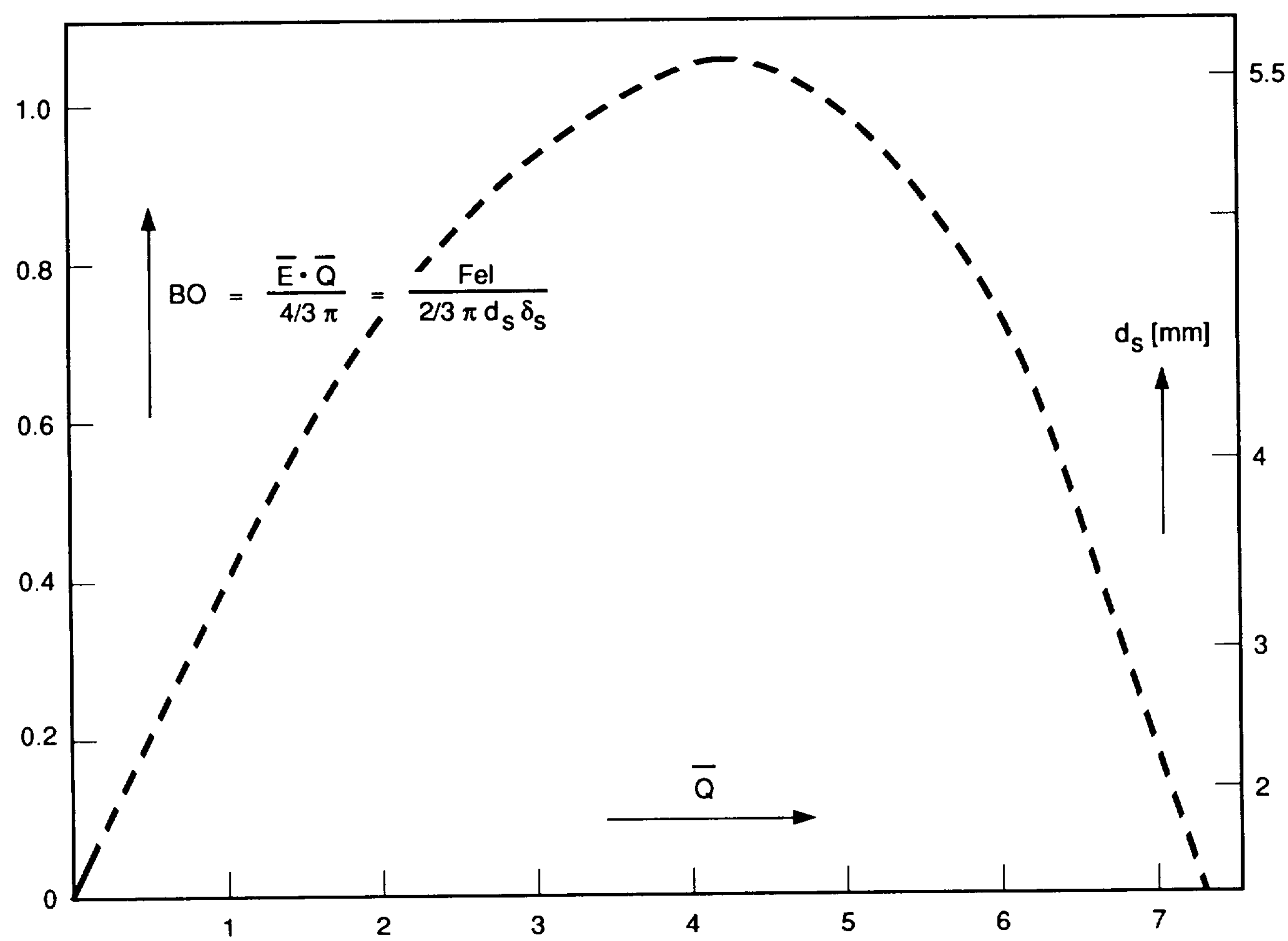

1.0
0.8
0.6
0.4
0.2
0
BO = $\frac{\bar{E} \cdot \bar{Q}}{4/3\,\pi} = \frac{Fel}{2/3\,\pi\, d_s\, \delta_s}$
$\bar{Q}$
1
2
3
4
5
6
7
d_s [mm]
5.5
4
3
2

Figure 6.

Characteristic parameters for the electrostatic levitation of water drops (1-G; with electrode separation of 3.2cm)

d_s [mm]:	1	2	3	4	5	5.5
Bo	0.034	0.136	0.307	0.545	0.85	1.03
$\bar{Q}$(min)	0.1	0.4	0.75	1.4	2.5	3.75
$\bar{Q}$(max)	7.2	7.05	6.8	6.4	5.65	4.75
U_2(min)[kV]	0.11	0.64	1.48	3.19	6.36	10.0
U_2(max)[kV]	8.2	11.4	13.4	14.6	14.4	12.7
U_2(opt)[kV]	2.4	3.4	4.1	4.75	5.3	5.56
U_1 (opt)[kV]	1.23	3.5	6.4	9.9	13.8	15.9

ELECTROSTATIC-ACOUSTIC HYBRID LEVITATOR

SPECIFIC FEATURES OF THE ELECTROSTATIC-ACOUSTIC HYBRID LEVITATOR

1) THE LEVITATOR CAN OPERATE EITHER AS ELECTROSTATIC, ACOUSTIC, OR HYBRID LEVITATOR. (FIG. 7)

2) HARDWARE COMPONENTS ARE SIMPLY INTEGRATED WITHOUT INTERFERENCE.

3) ELECTRONICS AND MECHANICAL HARDWARE ARE SIMPLE AND NEED NO CONTROL CIRCUITRY FOR POSITIONING, CALIBRATION AND TUNING.

4) LEVITATOR CAN OPERATE ON GROUND AND UNDER MICROGRAVITY CONDITIONS.

5) SINCE THE ACOUSTIC LEVITATOR PROVIDES STABILITY ARROUND THE PRESSURE NODE SUCH THAT

$$-1 < \sin(2k\Delta z) < 1,$$

THE ELECTROSTATIC FORCE (FIELD VOLTAGE, U_1) CAN BE VARIED WITHIN

$$U_{1,0}(1 - \phi_{s,ac}) < U_1 < U_{1,0}(1 + \phi_{s,ac})$$

WHERE $\phi_{s,ac}$ IS THE ACOUSTIC SAFETY FACTOR. (FIG. 8)

6) THE ACOUSTIC LEVITATION FORCE CAN BE REDUCED TO LESS THAN 5% OF ITS 1-G LEVEL RESULTING IN REDUCED CONVECTION FLOW (AS WELL AS A MASS AND HEAT-FLOW REDUCTION).

7) FLUID SAMPLE DEFORMATION BY ACOUSTIC FORCES (OBLATE) AND ELECTROSTATIC FORCES (PROLATE) CAN CANCEL OUT RESULTING IN SPHERICAL DROPS.

8) DROP OSCILLATIONS (TRANSLATIONAL AND SHAPE) CAN BE EXCITED BY MODULATION OF EITHER THE ELECTROSTATIC OR ACOUSTIC FIELD.

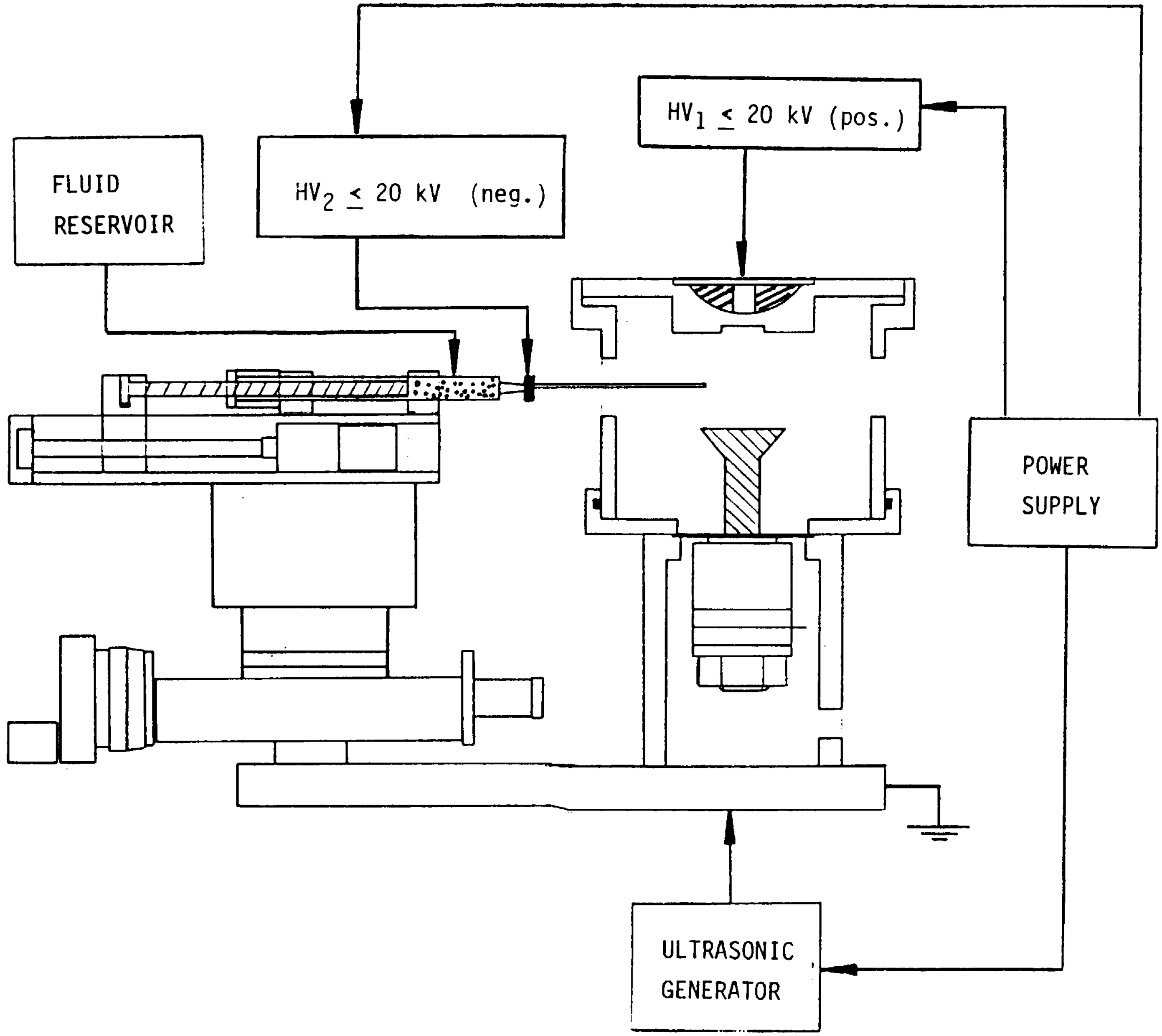


Fig. 7 : Block diagram of the Electrostatic-Acoustic-Hybrid Levitator

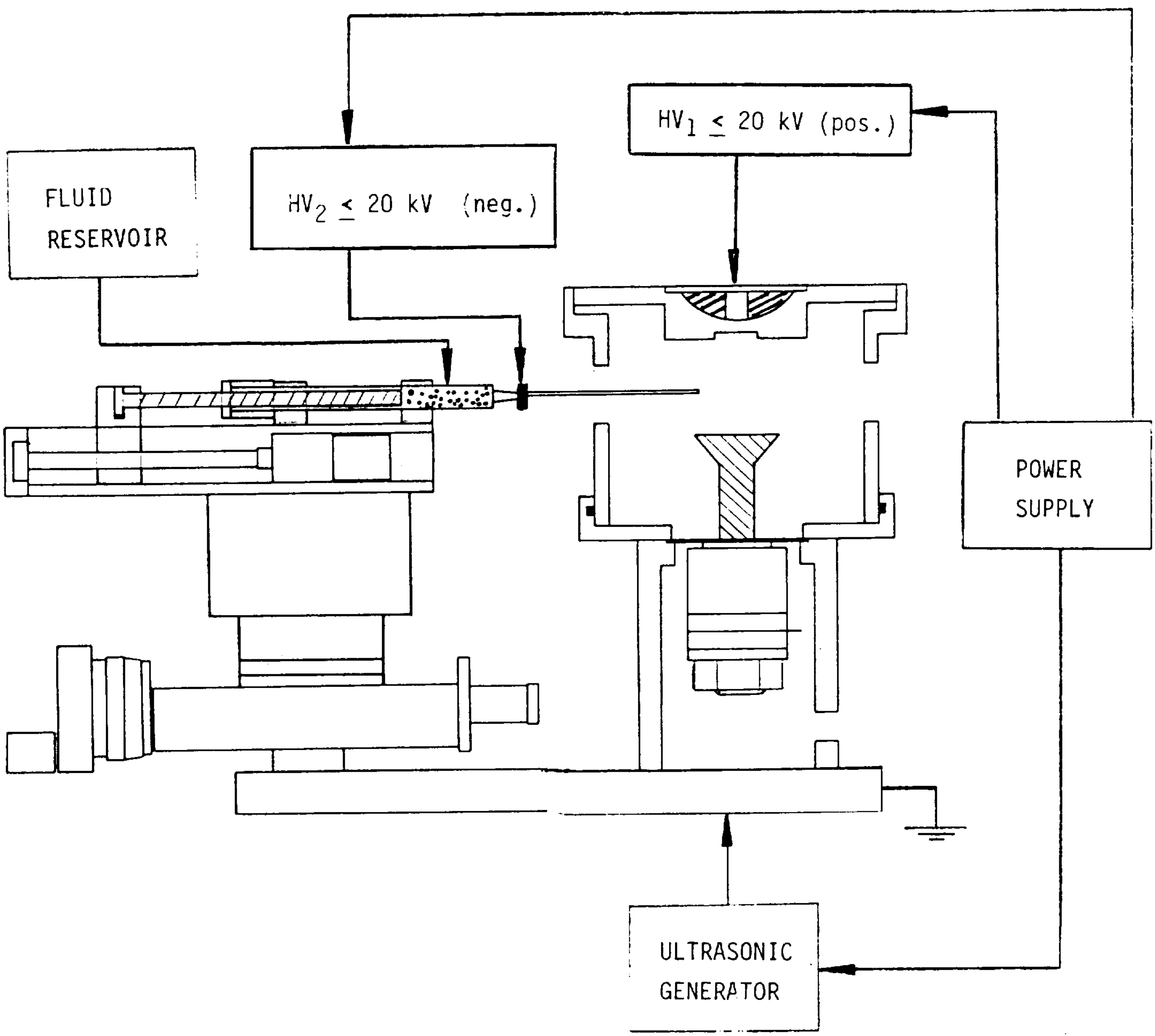


Fig. 7 : Block diagram of the Electrostatic-Acoustic-Hybrid Levitator

ADVANTAGES OF THE ELECTROSTATIC-ACOUSTIC HYBRID

- SIMPLE HARDWARE
- SPHERICAL DROPS
- FEASIBLE AT REDUCED GAS PRESSURE IN 1 G
- FEASIBLE FOR MOLTEN METALS (HIGH PRESSURE) IN 1 G
- EXCELLENT MICROGRAVITY SIMULATOR FOR ACOUSTIC LEVITATION
- GOOD FOR DISCHARGE MEASUREMENTS
- REDUCED FORCED CONVECTION, HEAT AND MASS TRANSFER
- MEASUREMENT OF SURFACE TENSION AND VISCOSITY IN 1 G
- MEASUREMENT OF THERMOPHYSICAL PROPERTIES IN 1 G
- EXTRAPOLATION OF G LEVELS EFFECTS OVER SEVERAL ORDERS OF MAGNITUDE
- SHAPE EFFECTS STUDIES ON SURFACE TENSION AND VISCOSITY