Chaotic Interaction of Bubbles under Forced Vibration in Microgravity

Mohammad Movassat
Nasser Ashgriz
Markus Bussmann

Mechanical and Industrial Engineering Department, University of Toronto

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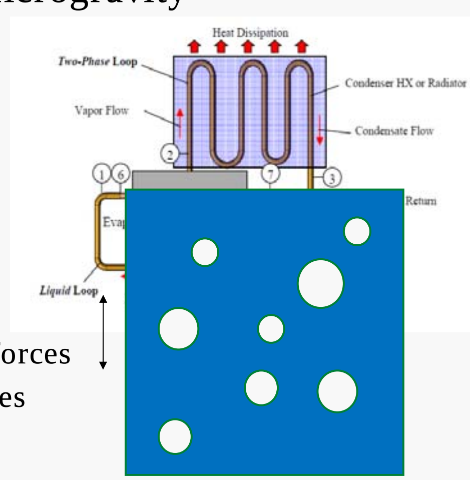
Motivation

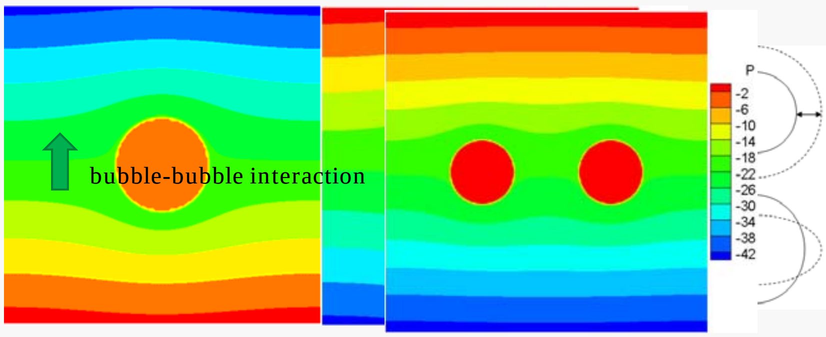
- Phase separation in microgravity
  - Applications:
    - Liquid recycling
    - Water purification
    - Thermal management
  - Methods:
    - Centrifugal force
    - Thermo-capillary force
    - Electric and magnetic forces
    - Vibration-induced forces



Oscillatory Body Force

3

oscillatory buoyancy force

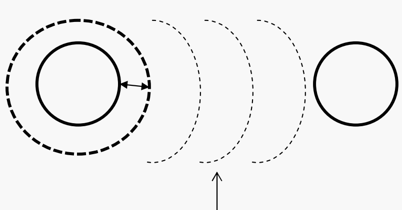


bubble-bubble interaction

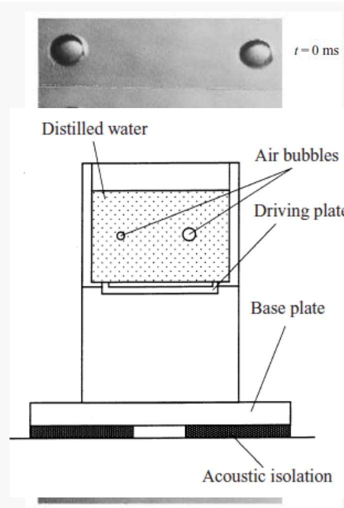
Bubble-Bubble Interaction

4

bubble-bubble interaction in acoustic fields



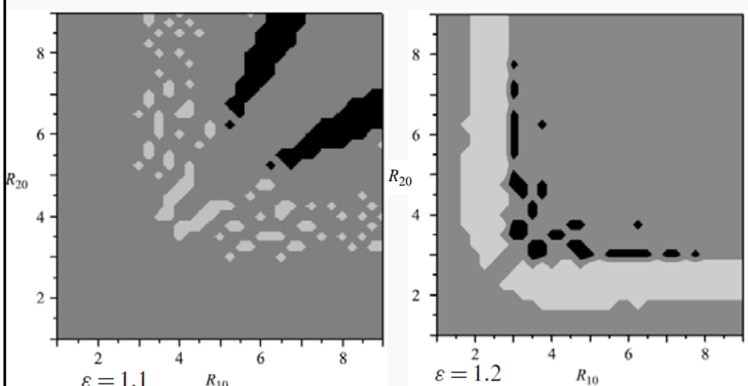
pressure wave ($\nabla p'$) from volume oscillation



from Barbat and Ashgriz-JFM (389)-1999

Interaction Map

5



$$P = \epsilon P_0 \sin(\omega_f t)$$

$$\omega_f = 20\ kHz$$

repulsion   attraction   stable

Pelekasis et al. JFM (500)- 2004

Translational Motion

6

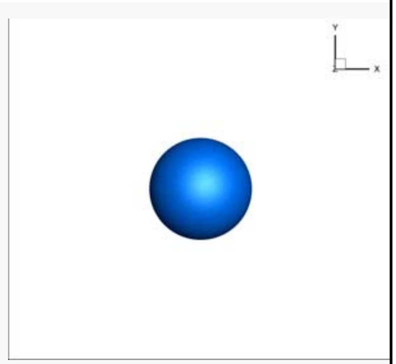
F_b = buoyancy force

F_d = drag force

F_a = added mass force

$$\sum F = F_b + F_d + F_a = m_b a$$

$$F_a = \begin{cases} C(\alpha,\beta)\dfrac{4}{3}\pi a^2 b\rho \dfrac{dU}{dt} & \text{Shape Change} \\ \dfrac{1}{2}\rho \dfrac{d}{dt}(UV) & \text{Volume Change} \end{cases}$$



R = 3 mm
f = 100 Hz
Ac = 0.2 mm

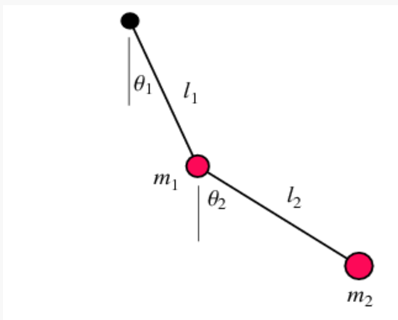
Oscillatory translational motion and shape/volume change are coupled

Int. J. of Engng. Sci. (19) -1981

Coupled Nonlinear Systems

7

- Double Pendulum problem
  - Two coupled nonlinear systems
  - Chaotic motion, sensitive to initial conditions



Objective

8

- Determine conditions under which bubble behavior becomes chaotic.
  - Study chaotic/regular behavior of bubbles under forced vibration
    - Identify regions where the bubble oscillation turns chaotic as a function of vibration amplitude, frequency, and bubble radius
    - Investigate if the chaotic motion can enhance the separation process or lead to the formation of smaller bubbles.

Objective

- Study bubble-bubble interaction under forced oscillation
  - Identify attraction, repulsion and oscillation regions based on vibration amplitude, frequency, and bubbles radii

Numerical Model

- Governing equations to be solved

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{V}\right) = 0$$

$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} = -\frac{1}{\rho} \nabla p + \frac{1}{\rho} \nabla \cdot T + \vec{F}_b$$

$$\vec{F}_b = A_c \omega^2 \sin(\omega t)$$

Two-dimensional-incompressible → Code developed by Bussmann et al.

Three dimensional-incompressible/ compressible → TransAT®

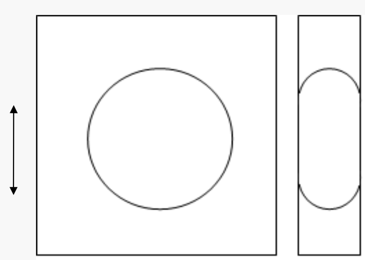
Numerical Model

$$\begin{cases} f = 0 & \text{gas} \\ 0 < f < 1 & \text{Interface} \\ f = 1 & \text{liquid} \end{cases}$$

$$\frac{\partial f}{\partial t} + \left(\vec{V} \cdot \nabla\right) f = 0$$

1	1	1	.68	0
1	1	1	.42	0
1	1	.92	.09	0
1	.85	.35	0	0
.31	.09	0	0	0
0	0	0	0	0

Comparison to Experiments



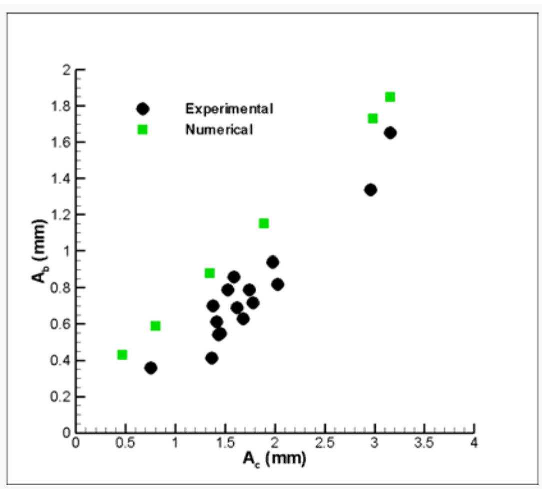
$R = 2.6\ cm$

$\rho_l = 1000\ kg/m^3$

$\rho_g = 1\ kg/m^3$

$\sigma = 0.022\ N/m$

$\omega = 2\pi f, f = 0.6\ Hz$

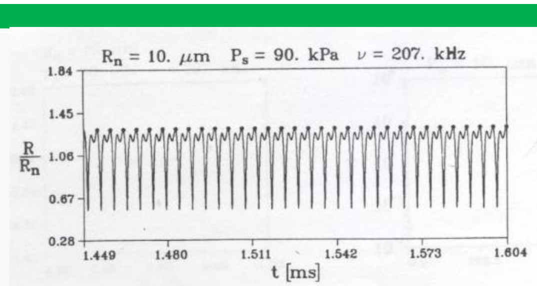


ISCAP project conducted during STS-85 mission in August 1997

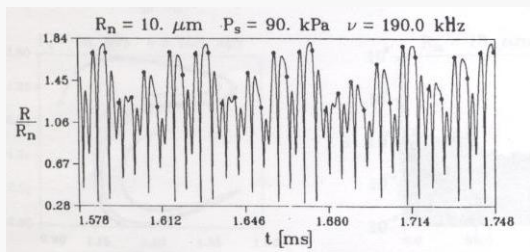
Regular VS Chaotic

13

Regular



Chaotic



Lauterborn and Parlitz,
J. Acoust. Soc. Am. (84)- 1988

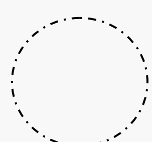
Shape Decomposition

14

$$r = R + \sum_{n=0}^{\infty} C_n(t)\, P_n(\cos(\theta)) = R + C_1(t)P_1(\cos\theta) + C_2(t)P_2(\cos\theta) + C_3(t)P_3(\cos\theta) + \cdots$$

Arbitrary shape

=



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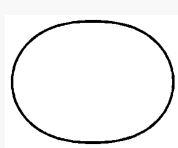
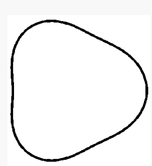
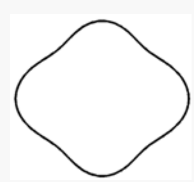




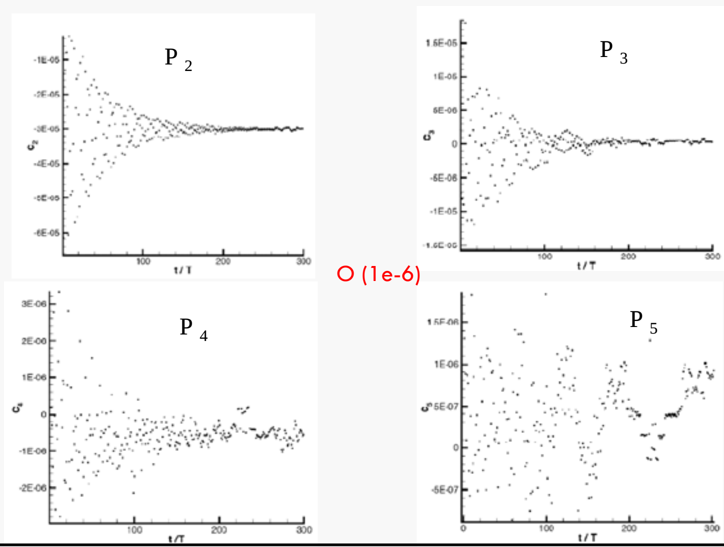


$P_2 = \frac{1}{2}(3cos^2 t - 1)$

$P_3 = \frac{1}{2}(5cos^3 t - 3)$

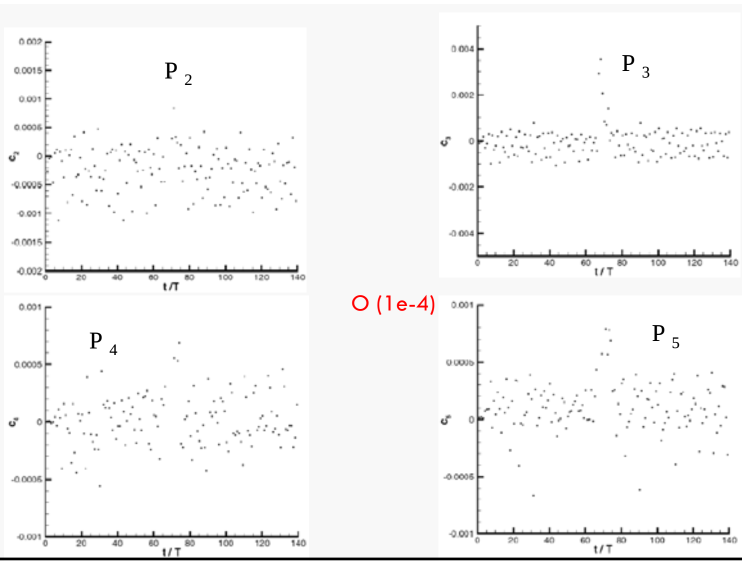
$P_4 = \frac{1}{8}(35cos^4 t - 30cos^2 t + 3)$

Regular Oscillation



R = 2 mm
f = 100 Hz
A_c = 0.1 mm

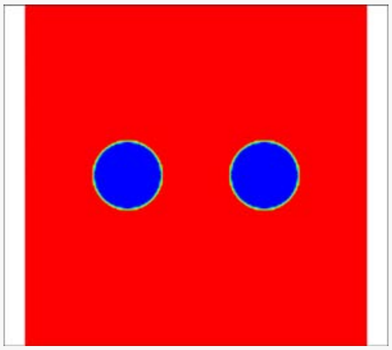
Chaotic Oscillation



R = 2 mm
f = 100 Hz
A_c = 0.2 mm

Bubble-Bubble Interaction

17



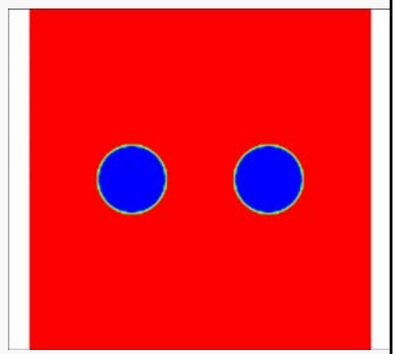
$\rho_l = 1000\ kg/m^3$

$\rho_g = 1\ kg/m^3$

$\sigma = 0.073\ N/m$

$f = 100\ Hz$

$R = 2\ mm$



$A_c = 0.1\ mm$

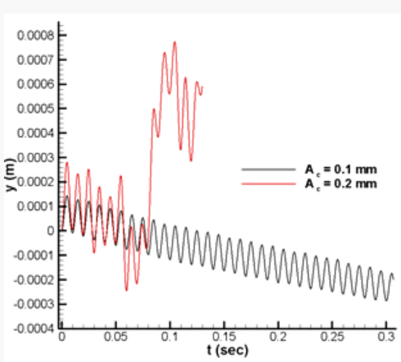
$A_c = 0.2\ mm$

Vibration Amplitude Effect

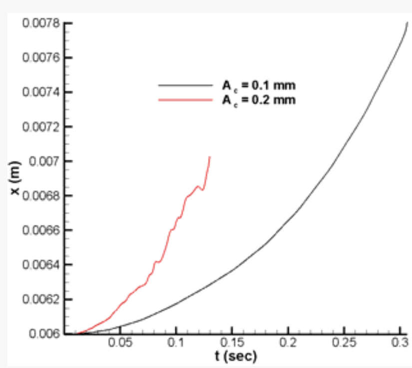
18

Vibration Amplitude Effect

f = 100 Hz, σ = 0.073 N/m, ρ_l / ρ_g = 1000/1



vertical position



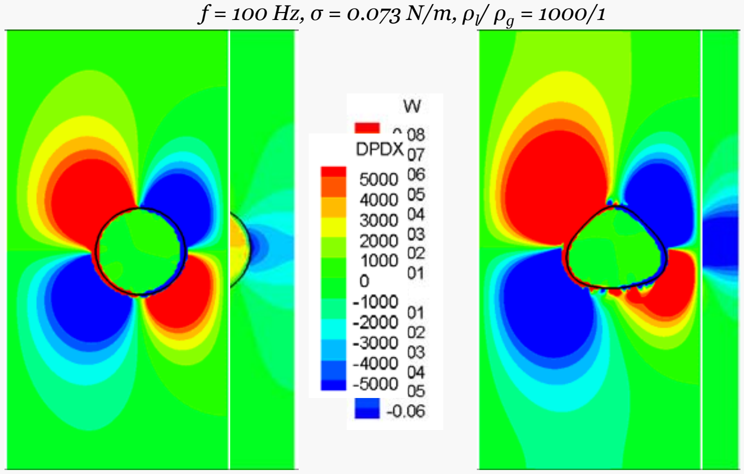
horizontal position

Left bubble motion

Vibration Amplitude Effect

Vibration Amplitude Effect- left bubble

f = 100 Hz, σ = 0.073 N/m, ρ_l / ρ_g = 1000/1



A_c = 0.1 mm

A_c = 0.1 mm

Vertical velocity at t=5.25 T (m/s)

Horizontal pressure gradient at t=5 T (Pa/m)

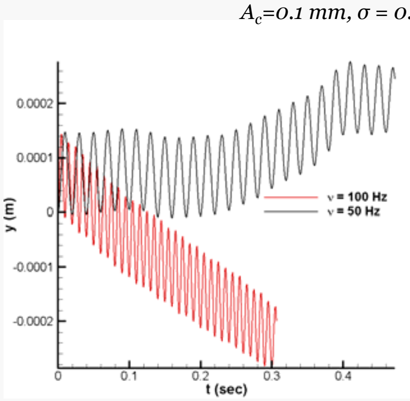
A_c = 0.2 mm

A_c = 0.2 mm

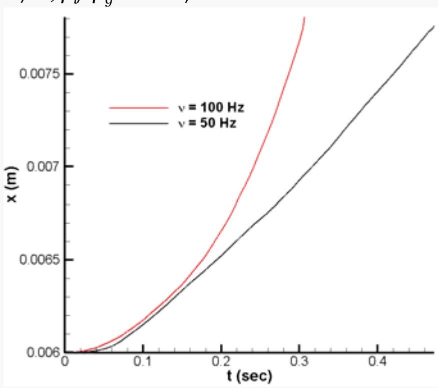
Vibration Frequency Effect

Vibration frequency Effect

A_c=0.1 mm, σ = 0.073 N/m, ρ_l / ρ_g = 1000/1



vertical position



horizontal position

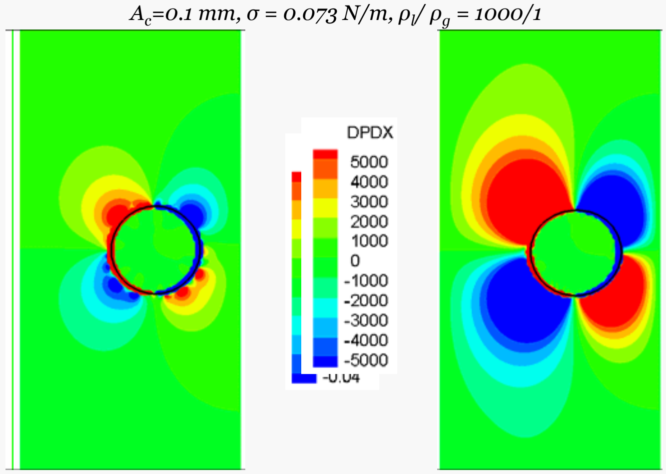
Left bubble motion

Vibration Frequency Effect

21

Vibration frequency Effect- left bubble

A_c=0.1 mm, σ = 0.073 N/m, ρ_l / ρ_g = 1000/1



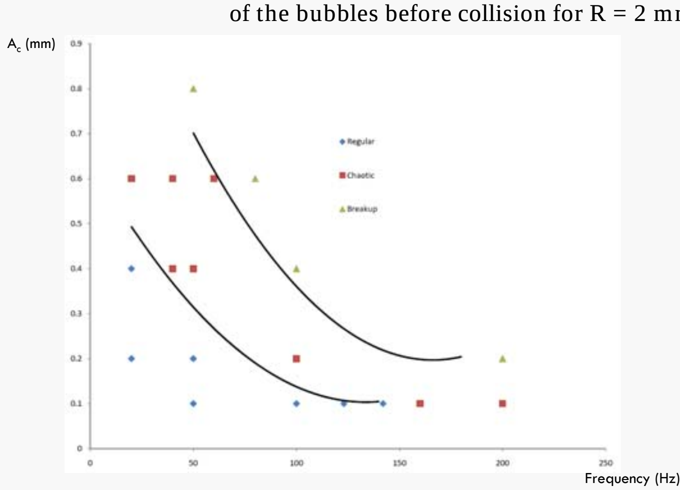
f = 50 Hz Horizontal pressure gradient at t=0.1 sec (Pa/m) f = 100 Hz

Vertical velocity at t=12.25T (m/s)

Bubble Behavior

22

Effect of vibration amplitude and frequency on the shape of the bubbles before collision for R = 2 mm



3D Results

t = 0 t = T t = 3T t = 5T t = 7T

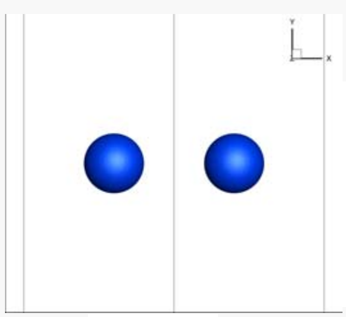
R = 2 mm, f = 100 Hz, Ac = 0.2 mm

t = 0 t = T t = 3T t = 5T t = 7T

R = 3 mm, f = 100 Hz, Ac = 0.2 mm

3D Bubble-Bubble Interaction

- Bubble-bubble interaction



$R = 2\ mm$

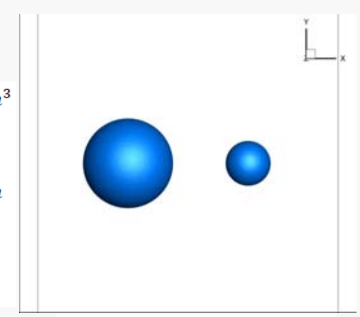
$\rho_l = 1000\ kg/m^3$

$\rho_g = 1\ kg/m^3$

$\sigma = 0.073\ N/m$

$f = 100\ Hz$

$A_c = 0.2\ mm$



$R_1 = 3\ mm \quad R_2 = 1.5\ mm$

Conclusions

25

- Oscillatory translational motion and shape deformation of bubbles are strongly coupled.
- This coupled system can become chaotic under certain conditions.
- The chaotic behavior is characterized based on the behavior of the Legendre polynomial coefficients which represent the shape of the bubble.
- The onset of chaotic behavior depends on the bubble size, vibration amplitude and frequency.

Conclusions

26

- In smaller bubble sizes, amplitudes, and frequencies surface tension force stabilizes the motion and prevents chaos.
- As a results of the flow fields developed around each bubble, bubble-bubble interaction occurs. In this study, outcome of the interaction was attraction.
- Higher vibration amplitude and frequency enhances the bubble interaction and attraction.
- Possibility of bubble breakup to smaller bubbles also increases in higher amplitudes and frequencies.

Thank You