天津大學
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# Magnetic Levitation

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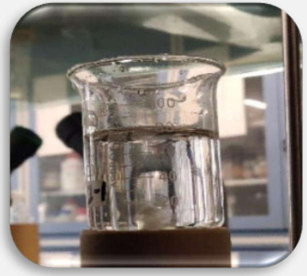
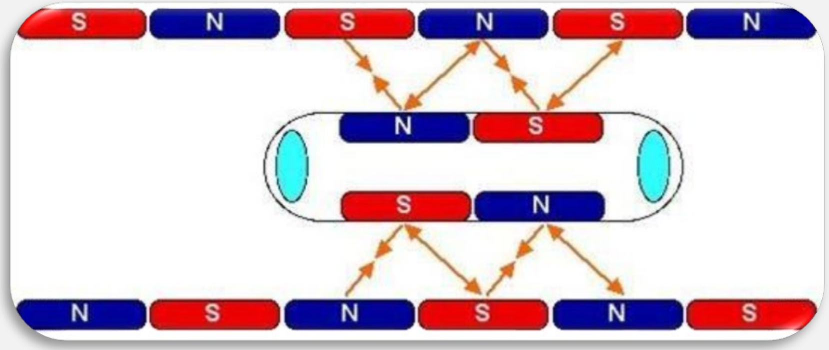
# 01 Background



**Magnetic Levitation**

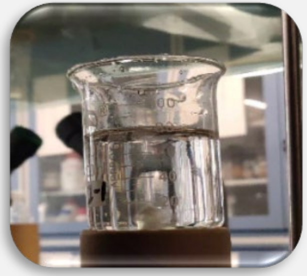
# Background




Magnetic levitation is a technology that applies a magnetic field to make an object overcome gravity and be in a stable equilibrium state.

- Application: Transportation, etc.
- Features: low friction, high upper speed limit, etc.
- Development Trend: looking for a relatively cheap and simple method of stable suspension, exploring the origin and dependent parameters that affect the dynamic stability of passive suspension.

# 02 Principle



**Magnetic Levitation**

## Principle

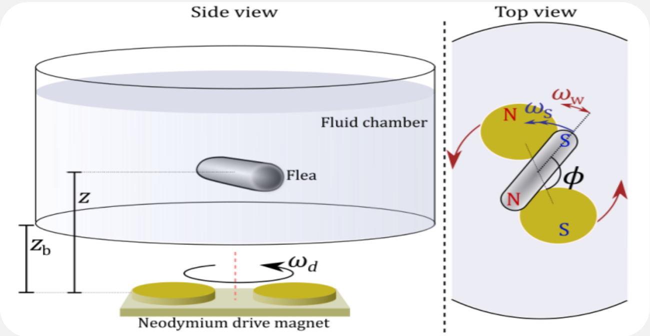
When at rest, the "stirring bar" and the permanent magnet are aligned in anti-parallel, the magnetic poles of different names are attracted to each other, and the phase angle $\varphi=\pi$.

The permanent magnet is dragged by the motor to rotate at an angular speed $w_d$.

The "stirring bar" rotates around the axis perpendicular to the longest axis, the rotation speed is $w_s <= w_d$, the phase angle is reduced ($\varphi<\pi$ ).

The driving angular velocity $w_d$ is increased to the critical threshold angular velocity.

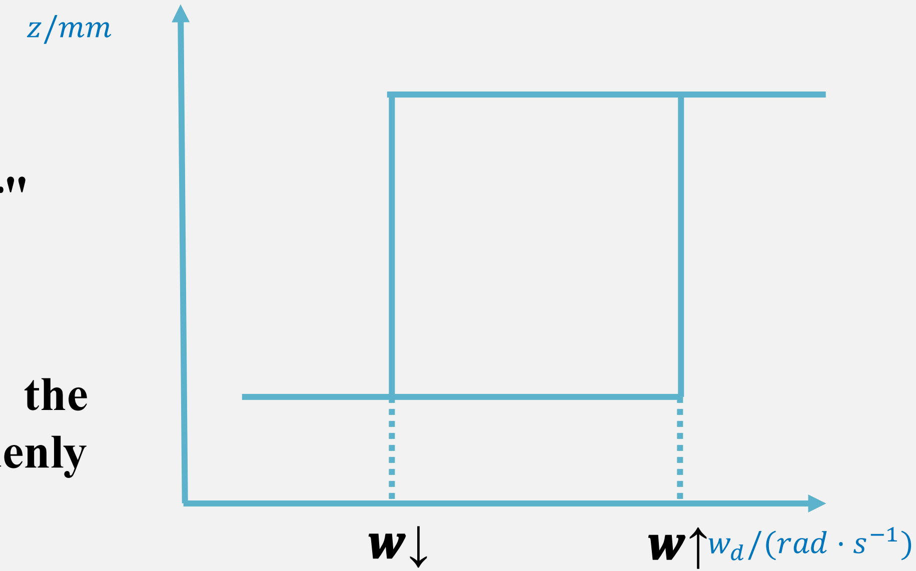
The viscous torque reduces the phase angle to within $\pi/2$, so that the repulsive magnetic force in the vertical direction becomes larger and larger.

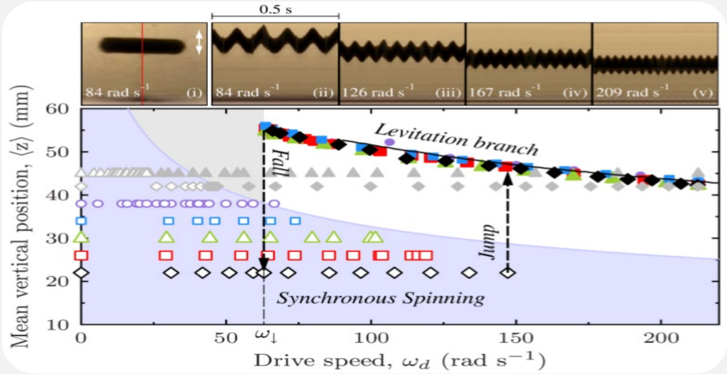



Due to the effect of viscous torque on its movement, the viscous torque (M) is changed by adjusting the driving speed ( $w_d$ ) and viscosity ($\eta$) of the fluid, and the initial inter-pole coupling is changed by driving the bottom height of the container above the magnet ($z_b$). Slowly increase $w_d$ to limit the inertia effect of the stirrer against angular acceleration.

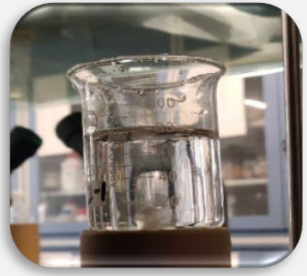
## Principle

- The average height $z$ of the "stirring bar" decreases with the increase of $w_d$.
- Impact Rising Angular Velocity $w\uparrow$:
  gradually increase $w_d$ to 146rad/s, the height of the "stirring bar" will suddenly rise to a height of approximately 45mm.
- Impact Descending Angular Velocity $w\downarrow$ :
  gradually decrease $w_d$ to 63rad/s, the height of the "stirring bar" will suddenly drop.
- It shows obvious hysteresis. Under ideal conditions such as $z_b$ and other conditions, the value of $w\uparrow$ is greater than $w\downarrow$.

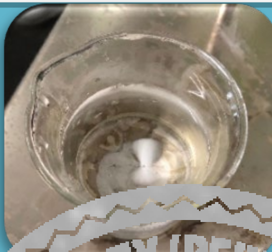


# 03 Process



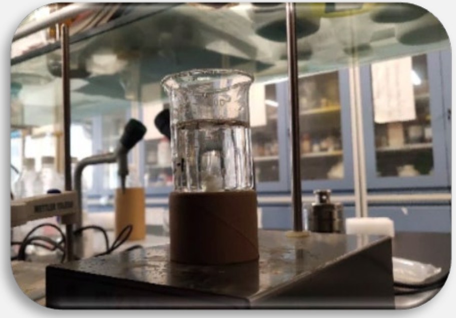
**Magnetic Levitation**

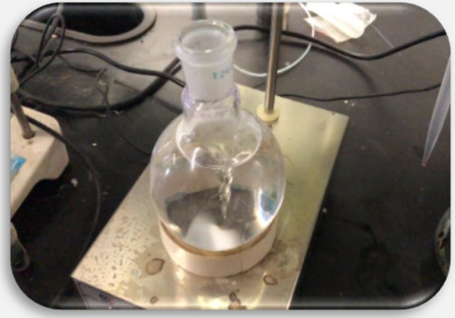


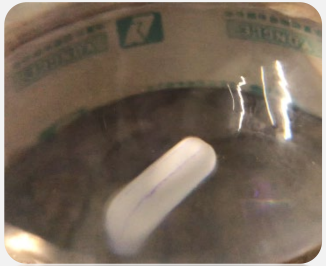
# Experiment Apparatus

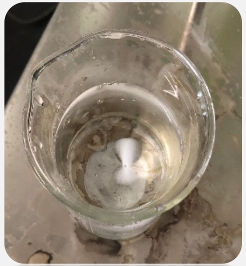
- Magnetic stirrer
- "Stirring Bar"
- Beaker (or flask)
- Liquids of different viscosities (Water, Dichloromethane, Toluene)
- Self-made instrument for measuring angular velocity

(Use the video to record the rotation of the "stirring bar", slow down the video, and count the number of rotations of the "stirring bar" in a period of time.)



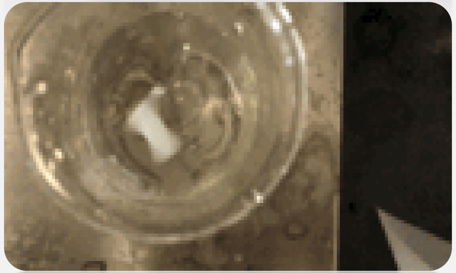






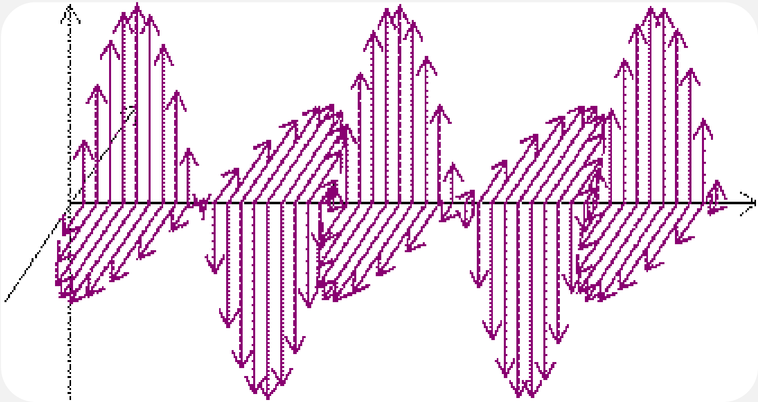
# Experimental Phenomena

- In low-viscosity liquids (such as water), when the magnetic stirrer reaches a certain speed, the "stirring bar" will be irregularly beaten, and vortices are prone to occur, which affects the observation of the " stirring bar" movement.
- For fluids with higher viscosity ($\eta >\approx 0.4$Pa.s) (such as dichloromethane, toluene, etc.) and $z_b$ is greater than the threshold ($z_b >\approx 4$cm), when the magnetic stirrer reaches a certain speed, the "stirring bar" will be bounced and finally stabilized a few centimeters from the bottom of the beaker.
- For $\eta \approx 0.4$Pa.s and for $z_b <\approx 4$cm, the magnetic repulsion force overcomes gravity, and the "stirring bar" jumps up until it is stably suspended a few centimeters above the bottom of the container.



# Experiment Analysis

**The dynamic balance analysis of magnetic levitation in fluid can be divided into two aspects: horizontal rotation and vertical axial runout, that is, the analysis of $\theta$ and $z$. After consulting relevant literature and inferring based on experimental data, we found some parameters that affect $\theta$ and $z$, such as driving angular velocity $w_d$, fluid viscosity $\eta$, the height of the beaker from the bottom $z_b$, and the radial position of the beaker.**



## $w_d$ Influences $\theta$

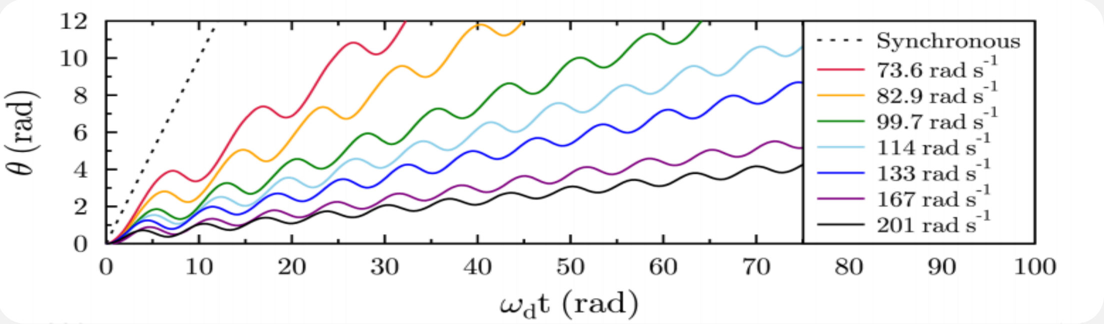
The angular motion $\theta(t)$ of the "stirring bar" is a combination of rotation and swing, in which the swing speed ($w_w$) increases with $w_d$, and the rotation speed ($w_s$) decreases with $w_d$.

The expression is as follows:

$$\theta = w_s t + A\sin(w_w t)$$

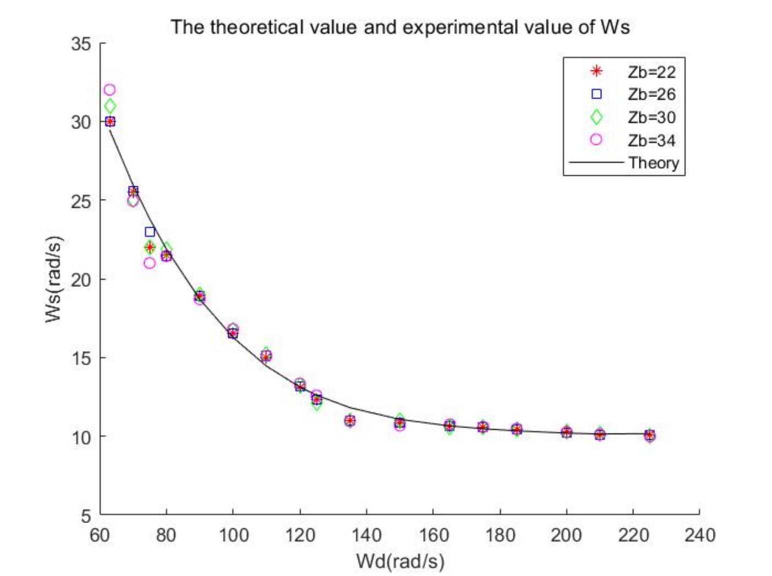
$A$ is the amplitude of the swing.

In the fitting equation, $w_s$, $w_w$ and $A$ value are all functions of $w_d$ and $z_b$.



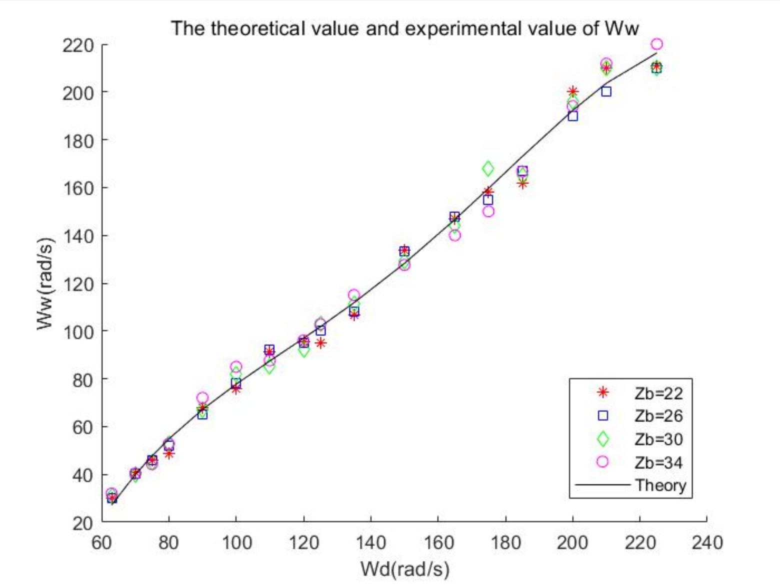
# $w_d$ Influences $w_s$

| $w_d/(rad \cdot s^{-1})$ | $w_s/(rad \cdot s^{-1})$ | | | | |
|---|---|---|---|---|---|
| | $z_b = 22$ | $z_b = 26$ | $z_b = 30$ | $z_b = 34$ | Theoretical Value |
| 63.000 | 30.000 | 30.000 | 31.000 | 32.000 | 30.000 |
| 70.000 | 25.500 | 25.600 | 25.000 | 24.950 | 26.000 |
| 75.000 | 22.000 | 23.000 | 22.000 | 21.000 | 23.000 |
| 80.000 | 21.500 | 21.450 | 21.870 | 21.448 | 21.500 |
| 90.000 | 18.890 | 18.886 | 18.979 | 18.700 | 18.500 |
| 100.000 | 16.550 | 16.500 | 16.710 | 16.800 | 16.900 |
| 110.000 | 15.000 | 15.100 | 15.200 | 15.100 | 15.100 |
| 120.000 | 13.100 | 13.190 | 13.231 | 13.350 | 13.500 |
| 125.000 | 12.290 | 12.340 | 12.100 | 12.590 | 12.600 |
| 135.000 | 11.022 | 11.025 | 10.999 | 10.965 | 11.034 |
| 150.000 | 10.839 | 10.845 | 10.987 | 10.679 | 10.700 |
| 165.000 | 10.658 | 10.632 | 10.588 | 10.753 | 10.762 |
| 175.000 | 10.546 | 10.545 | 10.599 | 10.598 | 10.598 |
| 185.000 | 10.440 | 10.455 | 10.446 | 10.479 | 10.444 |
| 200.000 | 10.265 | 10.255 | 10.278 | 10.263 | 10.269 |
| 210.000 | 10.116 | 10.110 | 10.123 | 10.126 | 10.137 |
| 225.000 | 10.103 | 10.105 | 9.994 | 9.998 | 10.110 |



# $w_d$ Influences $w_w$

| $w_d/(rad \cdot s^{-1})$ | $w_w/(rad \cdot s^{-1})$ | | | | |
|---|---|---|---|---|---|
| | $z_b = 22$ | $z_b = 26$ | $z_b = 30$ | $z_b = 34$ | Theoretical Value |
| 63.000 | 30.000 | 30.000 | 31.000 | 32.000 | 30.000 |
| 70.000 | 40.965 | 40.120 | 40.000 | 40.330 | 40.000 |
| 75.000 | 45.890 | 45.910 | 44.880 | 44.300 | 45.010 |
| 80.000 | 48.700 | 51.870 | 52.900 | 52.790 | 50.000 |
| 90.000 | 67.880 | 65.000 | 67.120 | 72.000 | 69.000 |
| 100.000 | 76.000 | 78.200 | 82.000 | 85.000 | 80.000 |
| 110.000 | 91.234 | 92.000 | 85.000 | 87.650 | 90.000 |
| 120.000 | 95.449 | 94.780 | 92.188 | 96.000 | 98.000 |
| 125.000 | 95.000 | 100.100 | 103.00 | 102.800 | 100.000 |
| 135.000 | 106.890 | 108.000 | 111.140 | 115.000 | 110.000 |
| 150.000 | 134.000 | 133.300 | 128.890 | 127.600 | 130.000 |
| 165.000 | 147.090 | 148.000 | 144.110 | 140.000 | 145.000 |
| 175.000 | 158.000 | 155.000 | 168.000 | 150.000 | 160.000 |
| 185.000 | 162.000 | 167.000 | 165.010 | 166.700 | 170.000 |
| 200.000 | 200.000 | 190.000 | 196.000 | 194.000 | 195.000 |
| 210.000 | 209.890 | 200.000 | 210.000 | 211.800 | 205.000 |
| 225.000 | 211.000 | 210.000 | 209.890 | 220.000 | 215.000 |



# $w_d$ Influences $\theta$

## Conclusion:

**After suspending, the angular movement of the "stirring bar" has nothing to do with the initial vertical position, and gradually decreases $w_d$, the "stirring bar" becomes unstable, and when $w_d = w\downarrow \approx 63$, $w_s = w_w$.**

## $w_d$, $\eta$ Influence $w_s$, $w_w$, $A$

$$I\ddot{\theta} + D\dot{\theta} - M(z)\sin(\theta - w_d t) = 0$$

$$D = 8\pi\gamma k\eta l^3$$

$$M(z) = \mu_0 m_d m_f \,/\, 4\pi z^3$$

$I$ is the moment of inertia of the "stirring bar", $D$ is the damping coefficient, $k \approx 0.212$, $l$ =12mm. γ is the increase in resistance caused by the proximity to the bottom of the container. $m_d$ and $m_f$ are the respective magnetic moments of the driving magnet and the "stirring bar". The constants $m_d$, $m_f$, $I$ and γ are all measured by experiments.

**The value of $\eta$ will affect the damping coefficient. When the liquid is determined, the value of $\eta$ will be determined accordingly.**

**When the average height $z$ of the "stirring bar" is constant:**

$$\theta = \omega_d t$$

$$\sin(\phi) = \omega_d \,/\, \omega\uparrow$$

$$\phi = \theta(t) - \omega_d t$$

$$\omega\uparrow = (1.14 \pm 0.04) \times \frac{M(z_b)}{D}$$

## $w_d, \eta$ Influence $w_s$, $w_w$, $A$

**Asynchronous movement after jumping up—damping pendulum driven by constant torque**

$$\begin{cases} w_d = \omega\downarrow \\ w_s = \omega_w \end{cases} \Rightarrow \begin{cases} \omega_w^2 = w_d^2 - \frac{3}{4}\omega\downarrow^2 \\ \omega_s + A\omega_w = \frac{\sqrt{3}}{2}\omega\downarrow \end{cases}$$

$$\Delta t = 2\pi / \omega_w,$$

**The angle of the "stirring bar":** $\Delta\theta_f = 2\pi\,\omega_s/\omega_w$

**The angle of the driving magnet:** $\Delta\theta_d = 2\pi\,\omega_d/\omega_w$

$$\Downarrow$$

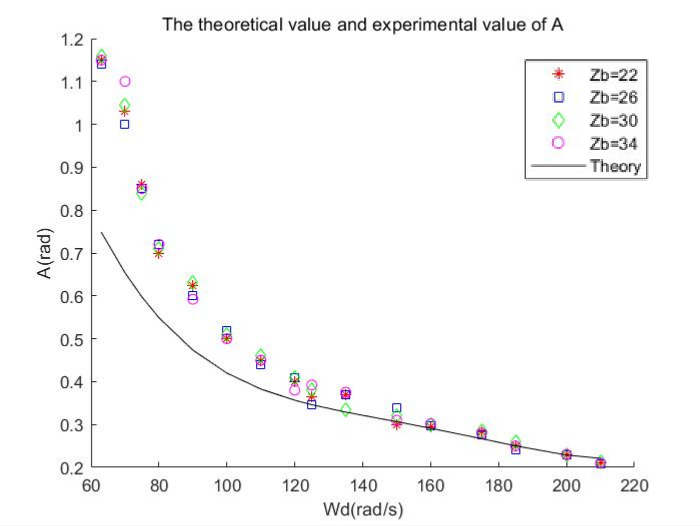
$$\Delta\theta_d = \Delta\theta_f + 2\pi$$

## $w_d$ Influences A

| $w_d/(rad \cdot s^{-1})$ | $A/(\mathrm{rad})$ | | | | |
|---|---|---|---|---|---|
| | $z_b = 22$ | $z_b = 26$ | $z_b = 30$ | $z_b = 34$ | Theoretical Value |
| 63.000 | 1.150 | 1.140 | 1.160 | 1.150 | 0.750 |
| 70.000 | 1.030 | 1.000 | 1.045 | 1.100 | 0.650 |
| 75.000 | 0.860 | 0.850 | 0.840 | 0.850 | 0.600 |
| 80.000 | 0.700 | 0.720 | 0.710 | 0.720 | 0.550 |
| 90.000 | 0.623 | 0.600 | 0.632 | 0.592 | 0.470 |
| 100.000 | 0.500 | 0.520 | 0.510 | 0.500 | 0.420 |
| 110.000 | 0.450 | 0.440 | 0.460 | 0.450 | 0.380 |
| 120.000 | 0.400 | 0.390 | 0.410 | 0.380 | 0.360 |
| 125.000 | 0.365 | 0.345 | 0.380 | 0.392 | 0.350 |
| 135.000 | 0.369 | 0.370 | 0.334 | 0.375 | 0.330 |
| 150.000 | 0.300 | 0.340 | 0.320 | 0.310 | 0.300 |
| 160.000 | 0.295 | 0.296 | 0.300 | 0.302 | 0.290 |
| 175.000 | 0.282 | 0.276 | 0.285 | 0.280 | 0.270 |
| 185.000 | 0.250 | 0.240 | 0.260 | 0.250 | 0.250 |
| 185.000 | 0.250 | 0.240 | 0.260 | 0.250 | 0.250 |
| 200.000 | 0.230 | 0.230 | 0.230 | 0.230 | 0.230 |
| 210.000 | 0.211 | 0.208 | 0.213 | 0.210 | 0.220 |
| 225.000 | 0.220 | 0.210 | 0.220 | 0.200 | 0.210 |

# Conclusion:

**Except where $w_d$ is small, the amplitudes are well fitted to the experimental data.**



## $w_d$ Influences $z$

$$\frac{z''}{g_1} + \frac{z'}{v_t} - \left(\frac{z_0}{z}\right)^4 cos(\theta - \omega_d t) + 1 = 0$$

- $g_1$ is the gravitational acceleration corrected for gravity and buoyancy.
- $v_t$ is the final translation speed of the "stirring bar", that is, the instantaneous speed of the "stirring bar" when the force (gravity, buoyancy, viscous force) of the "stirring bar" is balanced during the movement.
- $z_0$ is the theoretical equilibrium vertical distance when two magnets are aligned ($\varphi=0$) and at rest ( $w_d =0$).

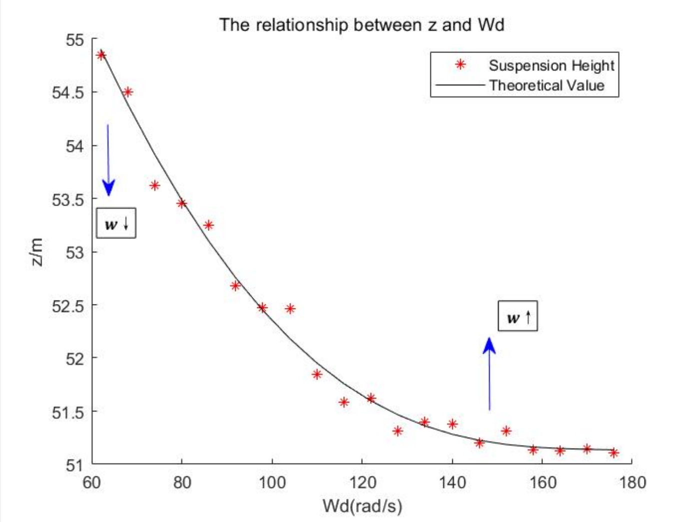
Among them, $v_t$ and $z_0$ are measured through experiments, and in the same experiment, that is, when factors such as the viscosity of the liquid do not change, $v_t$ and $z_0$ are fixed. Measured in this experiment $v_t$ =4m/s, $z_0$ =46mm.

# $w_d$ Influences $\theta$

| **Driving Speed** $w_d/(rad \cdot s^{-1})$ | Suspension Height (z/m) | Theoretical Value |
|---|---|---|
| 62 | 54.850 | 55.000 |
| 68 | 54.500 | 54.380 |
| 74 | 53.620 | 53.770 |
| 80 | 53.450 | 53.340 |
| 86 | 53.250 | 53.100 |
| 92 | 52.680 | 52.850 |
| 98 | 52.470 | 52.570 |
| 104 | 52.460 | 52.350 |
| 110 | 51.850 | 52.000 |
| 116 | 51.580 | 51.670 |
| 122 | 51.620 | 51.460 |
| 128 | 51.310 | 51.368 |
| 134 | 51.400 | 51.326 |
| 140 | 51.380 | 51.284 |
| 146 | 51.200 | 51.265 |
| 152 | 51.310 | 51.250 |
| 158 | 51.140 | 51.200 |
| 164 | 51.130 | 51.157 |
| 170 | 51.142 | 51.136 |
| 176 | 51.109 | 51.104 |

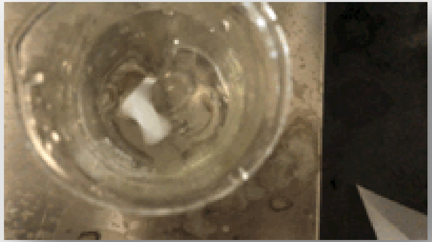
# Conclusion:

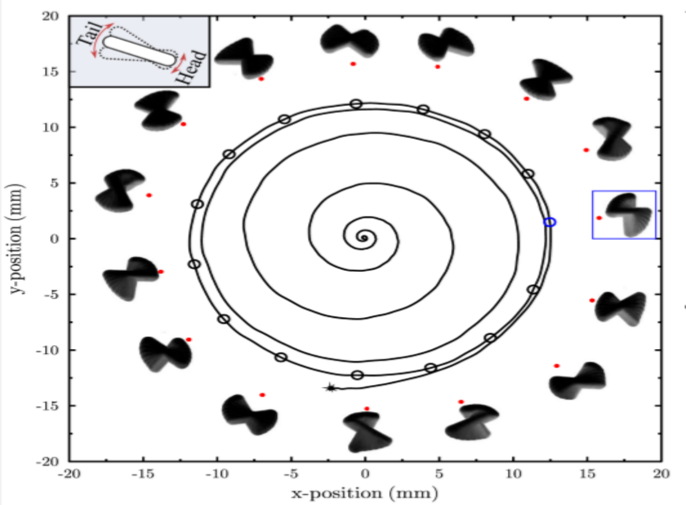
**The average levitation height between the numerical results and the experimental data is consistent. However, when the driving speed is too slow, ($w_d < w\downarrow$), the vertical stability is lost, that is, the "stirring bar" cannot be suspended.**



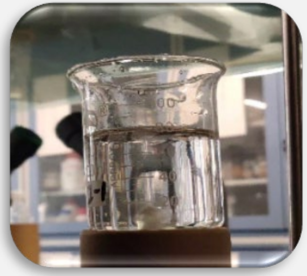
# Radial Position

The beaker on which the "stirring bar" is placed is quickly moved horizontally by 15mm, and it is observed that the "stirring bar" returns to the axis of the driving magnet along the spiral path, but in the process of returning, the "stirring bar" is eccentric, that is, the swing angle of one end (head) will be larger than the other end (tail), and the swept area will be larger.





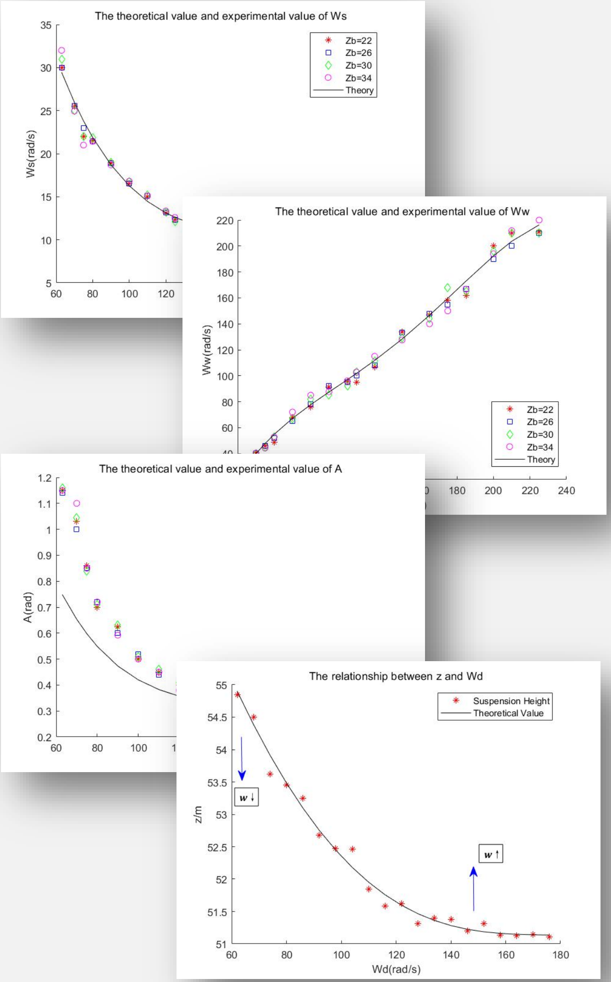
# 04 Conclusion



## Magnetic Levitation

# Conclusion

**According to our experimental process and related data, we found that the origin of the dynamic balance of the magnetic suspension in the fluid can be divided into two aspects: the horizontal rotation and the vertical axial runout, that is, the analysis of the dependent variables $\boldsymbol{\theta}$ and $\boldsymbol{z}$. After consulting relevant literature and inferring based on experimental data, we found that the driving angular velocity $\boldsymbol{w_d}$, fluid viscosity $\boldsymbol{\eta}$, the height of the beaker from the bottom $\boldsymbol{z_b}$, and the radial position of the beaker all affect $\boldsymbol{\theta}$ and $\boldsymbol{z}$. And we did a quantitative calculation on the influence of $\boldsymbol{w_d}$ and $\boldsymbol{z_b}$, and compared the measured experimental value with the theoretical value; qualitatively analyzed the influence of $\boldsymbol{\eta}$ and the radial position of the beaker.**



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*Thank you*