

A Study of Ultrasound on the Rise of Liquid in a Capillary Tube

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Abstract We study the sonocapillary effect driven by ultrasound by controlling variables. In this experiment, the guideway of the Michelson interferometer is placed vertically, so that the measurable accuracy is reduced to $10\ \mu\text{m}$. And we expand the observation range ($0\text{--}1000\ \mu\text{m}$), find that the sonocapillary effect has an obvious peak value near $30\ \mu\text{m}$; The sonocapillary effect gradually decreases as the gap increases and finally becomes stable. At the same time, the Fluent software is used to simulate the process. The dynamic mesh is introduced to simulate the ultrasonic action, and the simulation results are verified with the experimental results.

Keywords: the sonocapillary effect, rise performance, ultrasound, capillary tube, Fluent, simulate

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1. Introduction

The sonocapillary effect, the phenomenon of the height of liquid in a capillary tube increasing under the action of ultrasound, has been the focus of researchers. In existing literature, such as Hasegawa only studied the sonocapillary effect with gap (the distance between the nozzle of the capillary tube and the water tank) greater than $100\ \mu\text{m}$, and concluded that the rising height decreases (with invariable inner diameter) with the increase of outer diameter (7 sizes of capillary tube between $3\text{--}100\text{mm}$), and increases with the increase of frequency (18kHz , 38kHz , 83kHz), with no peak value found in the experiment [1]; Daisuke only simulated the ultrasonic pump. Due to the large data step length, it was concluded that the greater the gap, the greater the rising height, and no peak value was found, while the peak value of flow rate was around $30\ \mu\text{m}$ [2]; And there are no literature carried out from both experimental and simulative aspects.

As a basic concept in physics, ultrasound has a wide range of technical applications and teaching significance. Ultrasonic cavitation is also the basic principle of a large number of household appliances and industrial equipment, as well as an important part of undergraduate physics experiment course. However, it is not easy to directly observe the experimental phenomenon, so that students lack a visual understanding of ultrasonic cavitation. Cavitation in water can produce the sonocapillary effect, which can lead to the obvious experimental phenomenon of liquid rising in the capillary tube. Meanwhile, students can observe

obvious cavitation bubbles in the tube, so that they can have a more concrete understanding of the mechanism of cavitation. In addition, the instruments used in this experiment, such as Michelson interferometer and the capillary tube, are common equipment in the laboratory. It is not difficult to build the device, but the effect is obvious, which can be directly used in teaching, providing ideas for the experimental teaching of ultrasound for teachers in the future. Therefore, we carry out further research.

2. Experience

2.1. Experimental Setup



Figure 1. The practical experimental setup for height measurement

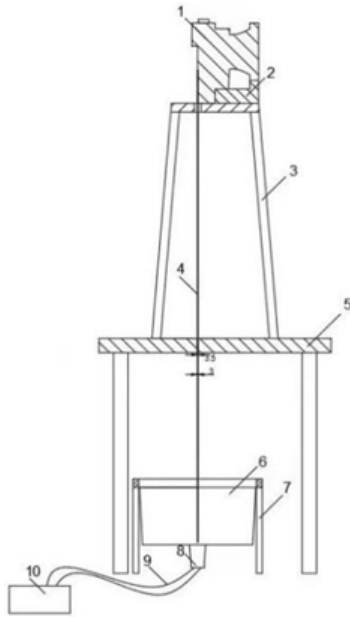


Figure 2. CAD drawing of experimental setup for height measurement. 1: Michelson interferometer(the guideway is placed along the vertical direction); 2: interferometer stents; 3: stents; 4: capillary tube; 5: table; 6: water tank; 7: water tank stents; 8: ultrasonic transducer; 9: wires; 10: ultrasonic generator

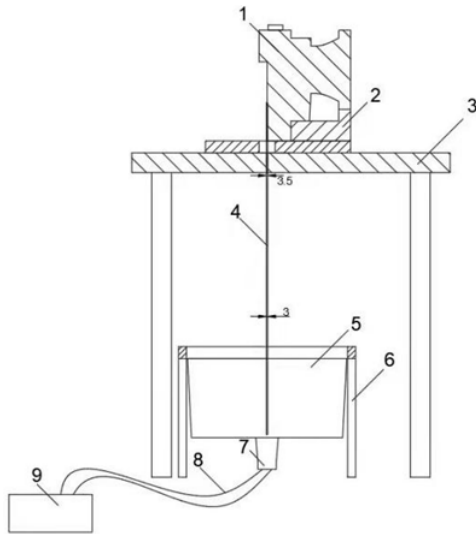


Figure 3. CAD drawing of experimental setup for flow rate measurement. 1: Michelson interferometer (the guideway is placed along the vertical direction); 2: interferometer stents; 3: table; 4: capillary tube; 5: water tank; 6: water tank stents; 7: ultrasonic transducer; 8: wires; 9: ultrasonic generator

Figure 1 shows the practical experimental setup, and Figure 2, Figure 3 shows the CAD drawing based on the scale of real setup.

The experimental setup for height measurement includes a WSM-200 Michelson interferometer, customized stents, capillary tubes, a marble table, a water tank, ultrasonic transducers, wires, a THD-T1 ultrasonic generator. The capillary tube passes through a 3.5mm hole on the table, which serves as restraint to reduce capillary sloshing.

The experimental setup for flow rate measurement removes the height stents from the height measurement setup and uses a hose to export the liquid into the graduated cylinder to measure the flow rate.

2.2. Experiment Settings

We take the distance between the nozzle of the capillary tube and the water tank (the whole text is referred to as gap) as the independent variable, the ultrasonic frequency, the capillary tube inner diameter and the liquid surface tension coefficient are changed respectively. And the sonocapillary effect is explored by observing the flow rate and the rising height of the liquid in the capillary tube. In order to simplify the description, the frequency of 25kHz, the inner diameter of 1mm, and the outer diameter of 3mm is called the standard state.

In order to control the influence of irrelevant variables, 1000ml pure water is added into the water tank in each experiment, and the position of the capillary tube in the water tank remained unchanged.

In order to achieve the 10 μ m adjustment of gap, we only use the mechanical structure of the interferometer. The capillary tube is fixed on the guideway of the interferometer with hot melt adhesive, and the step length of 10 μ m could be changed by adjusting its fine tuning handwheel.

Adjust the fine tuning handwheel of interferometer so that the capillary tube touches the water tank, and start recording data when the liquid droplets or the rising height of liquid are stable. We change ultrasonic frequency, capillary tube diameter and liquid surface tension coefficient, and record the flow rate (the flow rate measurement time of each group is consistent) or rising height with gap of 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000 (unit: μ m), 6 groups of data are recorded at the same gap.

2.3. The Experimental Results

2.3.1. Influence of Varying Gap on the Sonocapillary Effect

As shown in Figure 4, the gap is changed in the standard state, the flow rate measured at different gap is plotted as a continuous curve. It is found that the peak value of flow rate appears at about 30 μ m, and then decreases gradually with the increase of the gap, and becomes stable after 100 μ m.

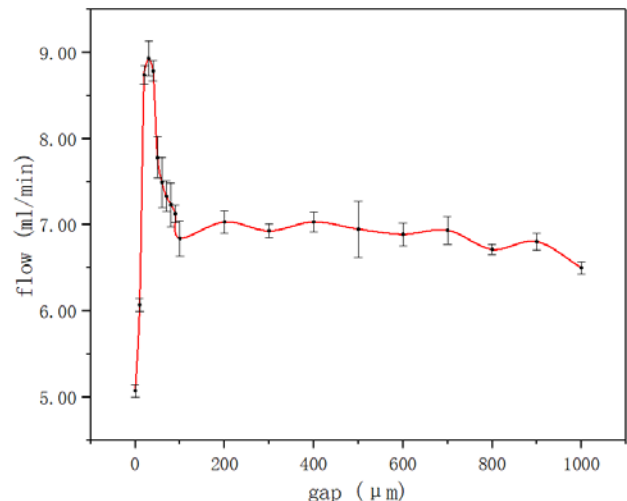


Figure 4. The relation between gap and flow rate

We record the rising height of the liquid in the capillary tube at different gap and plot the curve. The experimental results are shown in Figure 5. Similar to the flow rate, the peak value of rising height appears near 30 μm , and then decreases gradually with the increase of the gap, and becomes stable after 100 μm .

Because open water is not used in this experiment, the gap will limit the expansion of cavitation bubbles. When the gap increases from 0, the cavitation region enlarges and the radius of cavitation bubbles increases (the increase of the number of cavitation bubbles is not obvious), but the maximum cavitation bubble cannot be formed in the small gap range (the maximum radius of cavitation bubble

$$R_m = \frac{1}{4f} \sqrt{\frac{2P_m}{3\rho}}, \text{ where } P_m \text{ is the ultrasonic amplitude,}$$

ρ is liquid density, f is ultrasonic frequency [3]). The surface energy of the cavitation bubble is released after collapse, and the surface energy increases with the increase of the radius, and the rising height increases continuously. When the gap increases enough to form the maximum cavitation bubbles, the surface energy reaches the maximum and the rising height reaches the peak. With the increase of gap, the number of cavitation bubbles increases, and the secondary Bjerknes force between bubbles makes the maximum expansion radius decrease, which inhibits the expansion of bubbles [4]. At the same time, the shielding effect of cavitation bubble group on far-field bubbles is enhanced, and the far-field bubbles are less impacted by ultrasound, so it is difficult for them to expand and collapse, making the rising height decrease. When the surface energy of near-field bubbles is stable, the rising height does not change obviously.

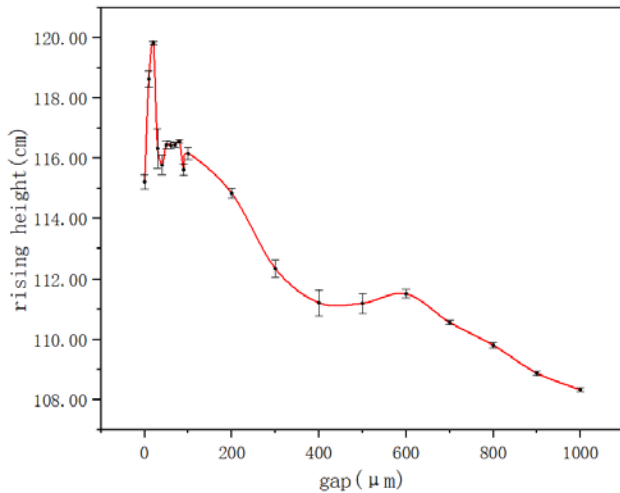


Figure 5. The relation between gap and rising height

2.3.2. Influence of Varying Other Parameters on the Sonocapillary Effect

2.3.2.1. Influence of Varying Ultrasonic Frequency on the Sonocapillary Effect

We control the diameter of the capillary tube (inner diameter is 1mm, outer diameter is 3mm) to remain unchanged, and conduct experiments with three frequencies of 20kHz, 25kHz and 28kHz respectively, and record the rising height of liquid at different gap. The

results are shown in Figure 6. During the experiments, the water in the water tank vibrated strongly when the large frequency transducer is used. The data show that there is a positive correlation between the frequency and the rising height, and the sonocapillary effect gradually enhances.

Liquid pressure fluctuates sharply due to turbulent pulse, and the fluctuation gradually enhances with the increase of frequency. When the frequency is about 20kHz, the cavitation bubbles begin to do nonlinear oscillate rapidly. At this time, with the increase of frequency, the bubble vibration amplitude increases, which accelerate the bubble expansion and collapse process [5], increase the surface energy released by the bubbles and the rising height.

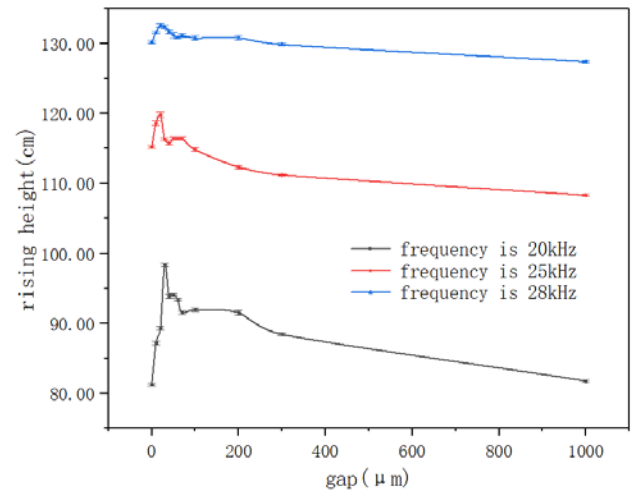


Figure 6. The relation between rising height and gap of different frequency

2.3.2.2. Influence of Varying Capillary Tube Diameter on the Sonocapillary Effect

We use capillary tubes of 0.3mm, 0.8mm and 1.0mm inner diameter (the outer diameter of all three is 3.0mm) respectively and a 25 kHz ultrasonic transducer. The rising height is recorded with the gap as the independent variable, as shown in Figure 7. For three capillary tubes of different diameters, the peak value all occurred around 30 μm , and the curve is flatter after 100 μm . At a fixed gap, the rising height is inversely related to the inner diameter, which is consistent with the theoretical equation

$$p = \frac{c^2 \rho u_0^2 \alpha^2}{(r_1 + r_2)g}$$

described in the literature, where r_1 and r_2 are the inner and outer diameter of capillary tube respectively, the static pressure p is positively correlated with the rising height [1].

In order to study the effect of capillary tube diameter on the flow rate, we use capillary tubes of 0.6mm, 0.8mm and 1.0mm inner diameter (the outer diameter of all three is 3.0 mm) respectively and a 25 kHz ultrasonic transducer, and the flow rate is shown in Figure 8. The flow rate curves of three kinds of capillary tubes reach their peak values around 30 μm . Within 0-1000 μm , the flow rate of the capillary tube with 0.8mm inner diameter is greater than that of the capillary tube with 0.6mm and 1.0mm inner diameter. The variation law of flow rate with different inner diameters will be further verified by simulation.

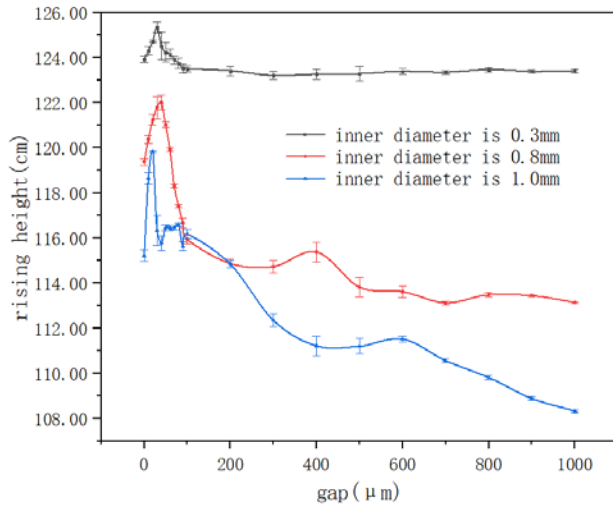


Figure 7. The relation between rising height and gap of different inner diameter

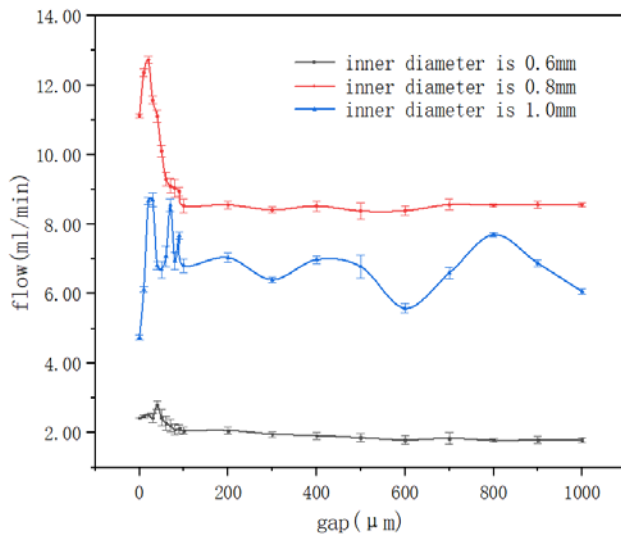


Figure 8. The relation between flow rate and gap of capillary tubes with different diameter

2.3.2.3. Influence of Varying Properties of the Liquid on the Sonocapillary Effect

We add different volumes of surfactant to pure water to change the surface tension coefficient of liquid. Their respective surface tension coefficients are shown in Table 1.

Table 1. Surface tension coefficient of liquid at 20°C

	Pure water	A laundry detergent
Surface tension coefficient of liquid at 20°C ($\times 10^{-3}$ N/m)	72.75	27.44

We change the surface tension coefficient by adding different amounts of detergent. We add 4ml and 8ml detergent to 1000ml pure water respectively and fully mix evenly. The rising height when the gap is 300 μ m in standard state is measured, and the results are shown in Table 2. With the increase of the volume of laundry detergent, the surface tension coefficient of the mixture decreases, the energy and rate of collapse of the bubbles

decrease, and the energy and velocity of the cumulative jets generated by cavitation decrease, so that the pressure at the pipe orifice decreases, and the rising height also decreases [6]. The theoretical and experimental results are in agreement.

Table 2. The rising height of mixed liquid in capillary tube with different detergent volumes

	Pure water	Add 4ml of the detergent	Add 8ml of the detergent
The rising height of mixed liquid (cm)	111.19	107.32	93.69

3. Theoretical Analysis

According to the VOF multiphase flow model in Fluent, considering the flow system composed of incompressible fluid, the momentum control Navier-Stokes equation can be written as follows:

$$\frac{\partial(\rho \vec{U})}{\partial t} = -\nabla P + \nabla \times (\mu \nabla \times \vec{U}) + \rho \vec{g} + \vec{F}_{SV}$$

Mass conservation equation is

$$\nabla \cdot \vec{U} = 0$$

where ρ is liquid density, t is time, $\vec{U} = (u, v, w)$ is fluid velocity, $P = P_0 \sin(\vec{k} \cdot \vec{r})$ is fluid pressure (where $k = \frac{2\pi f}{v}$, f is ultrasonic frequency, v is speed of sound in liquid), μ is dynamic viscosity coefficient, g is gravitational acceleration, F_{SV} is equivalent volumetric force of surface tension.

To solve the surface tension, we use the phase function F . The phase function is defined as the volumetric share of liquid phase in the studied local control volume, and its transport equation is

$$\frac{\partial F}{\partial t} + (\vec{U} \cdot \nabla) F = 0.$$

According to the continuity equation, the above equation can be further expressed as

$$\frac{\partial F}{\partial t} + \nabla \cdot (\vec{U} F) = 0, \frac{\partial F}{\partial t} + \frac{\partial (uF)}{\partial x} + \frac{\partial (vF)}{\partial y} = 0.$$

Assuming the phase function is known, the unit normal vector on the phase interface can be expressed as

$$\vec{n} = \frac{\nabla F}{|\nabla F|}$$

The surface tension can be expressed as

$$\vec{F}_{SV}(\vec{x}, t) = \sigma(\vec{x}, t) \cdot \vec{k}(\vec{x}, t).$$

Fluid velocity U can be solved in Fluent by the above equations. And the flow rate can be expressed as $Q = U \cdot S$, $S = \pi R^2$, where R is the radius of capillary tube. Then we simulate.

4. Simulations with Fluent

4.1. Geometric Model and Meshing

According to the practical experimental setup in the CAD software, we establish a two dimensional model, as shown in Figure 9. Using a dynamic mesh to write UDF function files, the sine function (we take vertical direction of capillary tube as the x-axis, the wave law of sound field acting on capillary tube can be described by plane wave equation: $p_1 = p_{ia} e^{i(\omega t - kx)}$). The practical application take the real part. So it can be described by the sine function) is used to simulate ultrasound. The grid regeneration method uses the Smoothing method.

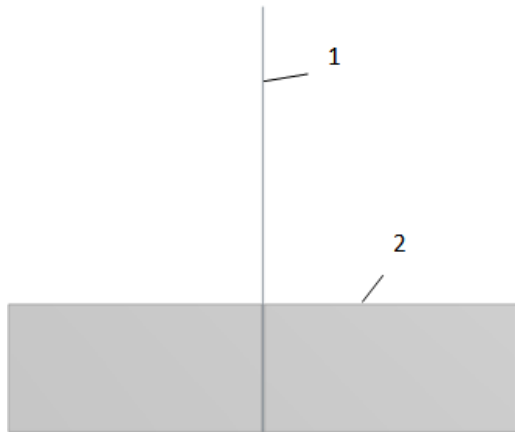


Figure 9. Schematic diagram of the two dimensional model of the experimental setup. 1: the capillary tube; 2: the water sink

4.2. Boundary Conditions and Solution

The VOF model is chosen for the simulation. Dynamic layers are used for the boundary conditions. The momentum is set by using the Second Order Upwind method. The iteration step is set to 2000 and the results are calculated after initialization.

4.3. Analysis of Results

To facilitate the calculation, we solve the height of the liquid level rise in 0.2s, and set the capillary inner diameters to 0.6mm, 0.8mm and 1mm respectively, and the gap to 10, 20, 30, 40, 50, 60, 200, 400 and 600 (units: μm). Then we calculate the flow rate of three tubes based on theoretical equations. The results for the three tubes are shown in Figure 10, with all achieving their peak values at $50\mu\text{m}$. And in the range of 0-1000 μm , the capillary tube with 0.8mm inner diameter has the largest flow rate, and that of the capillary tube with 0.6mm inner diameter is the smallest.

The simulation results are consistent with the overall trend of the experiment, but the peak value of the simulation is at $50\mu\text{m}$, while the peak value of the experiment is around $30\mu\text{m}$. The reason is that the fluid will flow back near the pipe orifice, and this backflow will be limited by the viscous effect of small gap, while large gap is not limited [2]. The experimental results are close to the simulation results when the gap is less than $30\mu\text{m}$, and the liquid reflux effect is more noticeable in the

experiments when the gap is greater, which leads to errors between the experimental and simulated results. In addition, in the simulation we set up a multi-layer grid at the bottom of the capillary tube and the bottom of the water sink as shown in Figure 11. The dynamic mesh applied to the bottom of the sink results in the reduction of the number of multiple mesh layers in direct contact with it. The impact on the number of layers of the grid on the small gap is significantly greater than the impact on the large gap. The above reasons cause a discrepancy between the experimental and simulated peak value, but in essence there is no contradiction between the two.

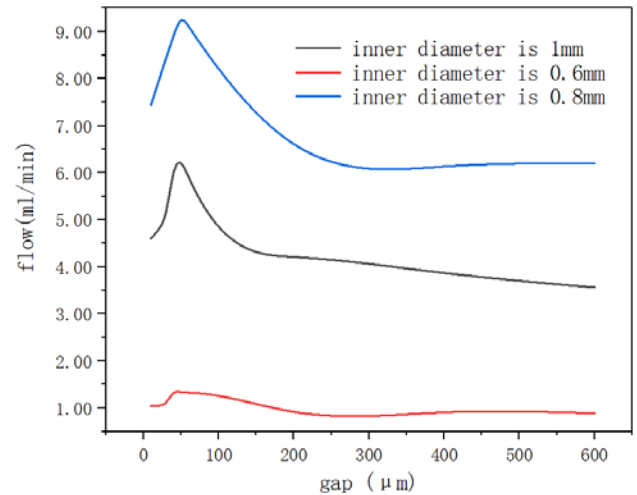


Figure 10. The simulated relation between flow rate and gap of capillary tubes with different diameter



Figure 11. Schematic diagram of the simulated two dimensional model with partial structural meshing.

5. Conclusions

The existing literature had not measured the gap within $100\mu\text{m}$ in detail, and no peak was found for the rising height, and lacked the mutual confirmation of experiment and simulation. By placing the interferometer vertically and using its own mechanical structure, we narrow the step length, measure the data every $10\mu\text{m}$ in the further expanded observation range (0-1000 μm), and use many frequencies (20kHz, 25kHz, 28kHz) and capillary tubes with different inner diameters (0.3mm, 0.6 mm, 0.8 mm, 1.0 mm) that had not been done yet before to conduct experiments. It is found that the rising height and the flow rate have obvious peak when the gap is $30\mu\text{m}$, and tend to be stable after $100\mu\text{m}$. At the same time, with the simulation by Fluent software, the rule of the rising performance of ultrasonic micropump is obtained, which is consistent with the experiment.

The experiment is simple in its execution and equipment, yet can provide profound insight into

fundamental concepts in acoustics, which can be incorporated into undergraduate students' learning plans for ultrasonic properties. At the same time, this experiment can also bring students a wide range of experimental skills and basic simulation skills training, including data processing, constructing the simple simulation model and so on. In addition, we pioneer the use of The Michelson interferometer as a distance adjustment tool, which makes it easy to change the distance at the level of $10\mu\text{m}$, and makes it possible to expand the content based on this experimental setup.

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