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高校内での微小重力実験:
実験装置の改善，音の立体的な可視化等の実験

Microgravity Experiments in High School: Apparatus Improvements and Three-Dimensional Sound Visualization Experiments

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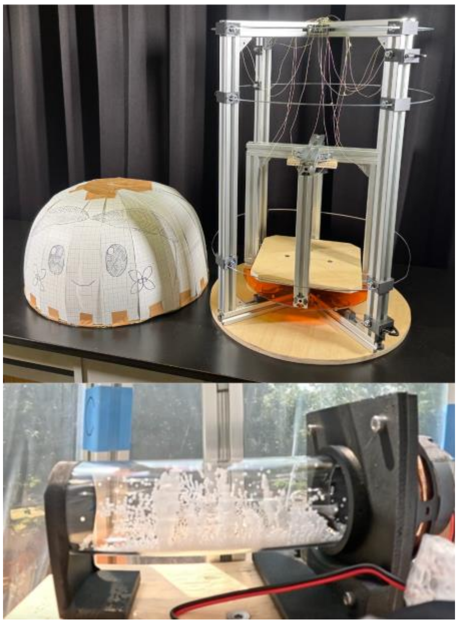

Abstract: The Zero-Gravity Experiment Team at Tokyo Gakugei University Senior High School has been developing an experiment apparatus for achieving microgravity environments within the high school and conducting microgravity experiments. TGμ-DS2, a drag-shield-type drop experiment apparatus, was developed as the second-generation model to achieve a high-quality microgravity environment at low cost. Improvements from the previous model eliminated contact-induced vibrations, enabling a stable microgravity environment at the 10^{-3}–10^{-2} g level for approximately 1.0 s. The development cost was approximately 200,000 JPY, less than 1/100 of the cost of conventional microgravity experimental methods. In a three-dimensional visualization experiment of acoustic standing waves, clear images of the spatial structure of the sound pressure distribution under microgravity conditions were obtained. The results highlighted the importance of setting appropriate sound pressure levels in microgravity. These outcomes demonstrate the potential of TGμ-DS2 to facilitate diverse microgravity experiments in educational and research settings at significantly reduced cost.

Keywords: Microgravity Experiment; Drop Tower; Free Fall Apparatus; Low-Cost Experimental Platform; Acoustic Standing Wave; Three-Dimensional Visualization; Kundt's Tube

1. Introduction

In recent years, with the realization of private space tourism, the utilization of outer space is rapidly becoming more accessible. Along with this expansion of space utilization, the importance of fundamental research utilizing microgravity environments is increasing. However, current microgravity experiments face challenges of high costs and limited accessibility, such as experiments on the ISS (costing tens of millions of JPY) and parabolic flights using aircraft (costing several million JPY).

Against this background, our research team aims to establish a low-cost microgravity experimental environment that can be easily utilized by educational and research institutions. In particular, with a view toward realizing fundamental scientific experiments for future space habitation, we have been developing a simple and inexpensive drag-shield-type drop experiment apparatus.

At the 36th Japan Society of Microgravity Application (JASMAC-36) in 2024, we reported on the first prototype of our drag-shield-type drop experiment apparatus. [1] This apparatus adopted a dual structure consisting of a drag shield to reduce air resistance and an inner capsule for conducting experiments. However, a problem was identified where unintended contact occurred between the two capsules during the drop, disturbing the microgravity environment. In this study, we implemented optimization of the apparatus, including enlargement of the drag shield, to resolve this issue.

Furthermore, as an application of this apparatus, we are conducting three-dimensional visualization experiments of acoustic standing waves in a microgravity environment. Conventionally, visualization of acoustic standing waves, as exemplified by Kundt's tube experiments, has been limited to two-dimensional planes due to the influence of gravity. In a microgravity environment, particles can freely distribute in three-dimensional space, enabling direct observation of the three-dimensional structure of acoustic standing waves. This is expected to yield significant results from both educational and fundamental research perspectives in acoustic physics.

In this paper, Section 2 describes the details and performance evaluation of the improved drag-shield-type drop experiment apparatus, Section 3 presents the methods and results of the three-dimensional visualization experiments of acoustic standing waves, Section 4 discusses future prospects, and Section 5 presents the conclusions.

2. Improvement of Drag-Shield-Type Drop Experiment Apparatus

2.1. Basic Configuration

In the TGμ-DS1 experiment, the inner capsule tumbled during its descent, causing it to make contact with the drag shield. This contact degraded the quality of the microgravity environment (Fig. 1). Consequently, modifications were made to the apparatus to address this issue. All drop tests were conducted from the third floor of the high school building (drop height ≈ 10 m).

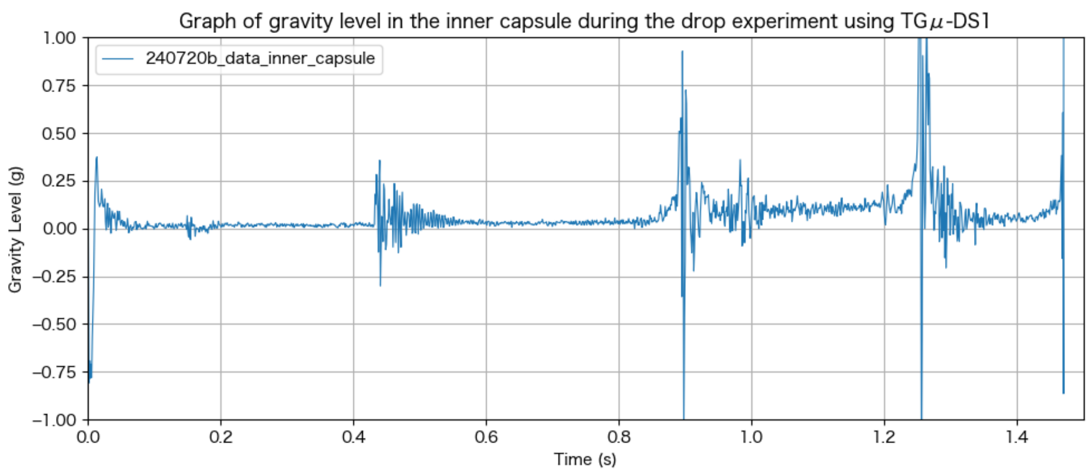

Figure 1. Graph of gravity level in the inner capsule during the drop experiment using TGμ-DS1

2.2. Improvements

The primary improvement was the enlargement of the drag shield. The clearance between the inner capsule and the drag shield was increased from 25 mm to 50 mm on each side (Fig. 2). Additionally, to enhance durability, the thickness of the aluminum frame was increased from 20 mm to 30 mm. Figure 3 shows TGμ-DS2.

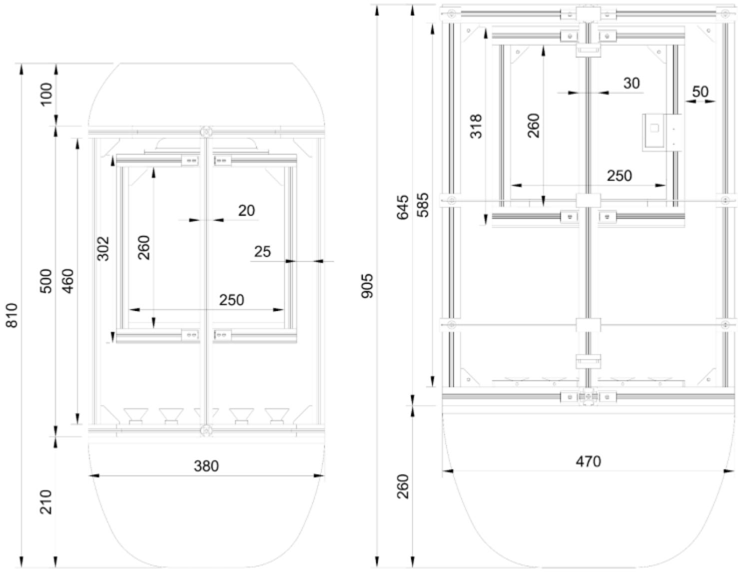

Figure 2. Size comparison between TGμ-DS1 and TGμ-DS2 (all dimensions in mm)

Figure 3. TGμ-DS2 created in CAD and rendered

2.3. *Performance Evaluation*

As a result, no contact between the inner capsule and the drag shield was observed in either condition (with or without the experimental equipment installed in the inner capsule). The drag-shield-type drop apparatus achieved a stable microgravity environment, with average absolute acceleration of 10^{-3}–10^{-2} g sustained for 1.0 s, consistent across both conditions (see Fig. 4).

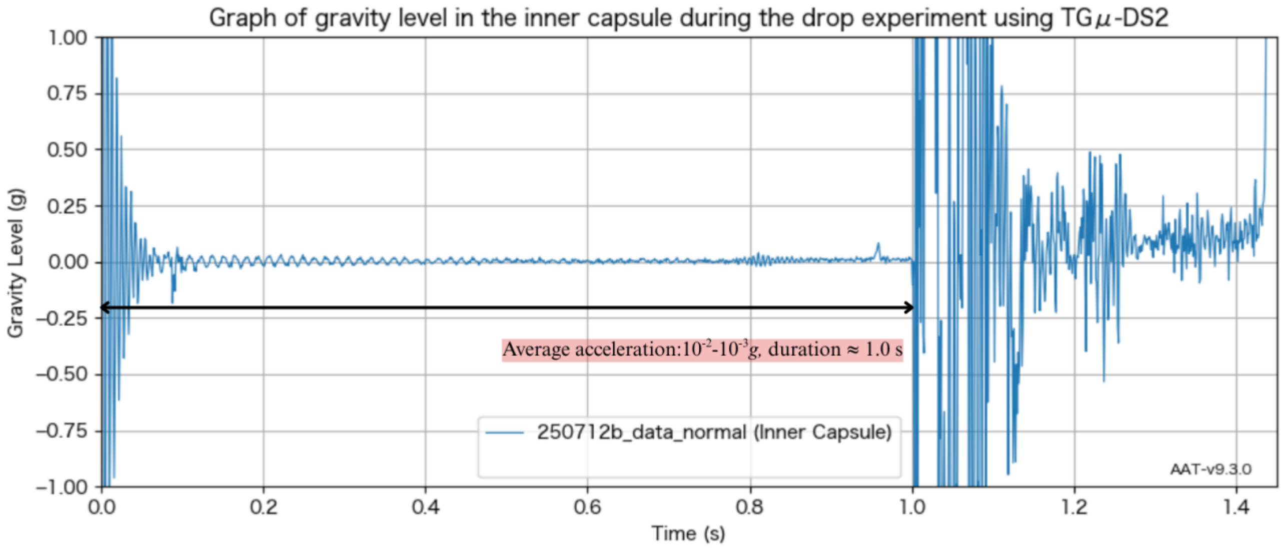

Figure 4. Graph of gravity level in the inner capsule during the drop experiment using TGμ-DS2

3. Three-Dimensional Visualization of Acoustic Standing Waves

3.1. *Experimental Principle*

The principle is based on acoustic resonance in tubes. When sound waves of a specific frequency are introduced into a tube, resonance occurs within the tube. It is known that when low-density particles are placed inside the resonating tube, they accumulate at either nodes or antinodes. Specifically, polystyrene particles have been observed to accumulate at antinodes.[2)] When Kundt's experiment is conducted on Earth, striped patterns form according to the sound wave amplitude, as shown in Fig. 5.

On Earth, due to gravitational effects, the striped patterns spread in a planar fashion. However, in a microgravity environment where gravity is significantly reduced, polystyrene particles are expected to distribute three-dimensionally.

Figure 5. Kundt's experiment under terrestrial gravity conditions [3)]

3.2. *Experimental Setup*

The experimental equipment consisted of a tube measuring 150 mm in length, with an outer diameter of 50 mm and an inner diameter of 46 mm. The speaker specifications were 20 W rated power and 40 W maximum power. The tube was configured as a closed-end tube, with only the connecting components fabricated using a 3D printer. The fundamental frequency of 996 Hz was determined experimentally rather than through theoretical calculation. An illustration of the equipment, comprising a CAD-based rendering without the speaker and a corresponding technical drawing, is shown in Fig. 6. Video recording was conducted using a GoPro HERO13 Black at 240 fps with 2.7K resolution.

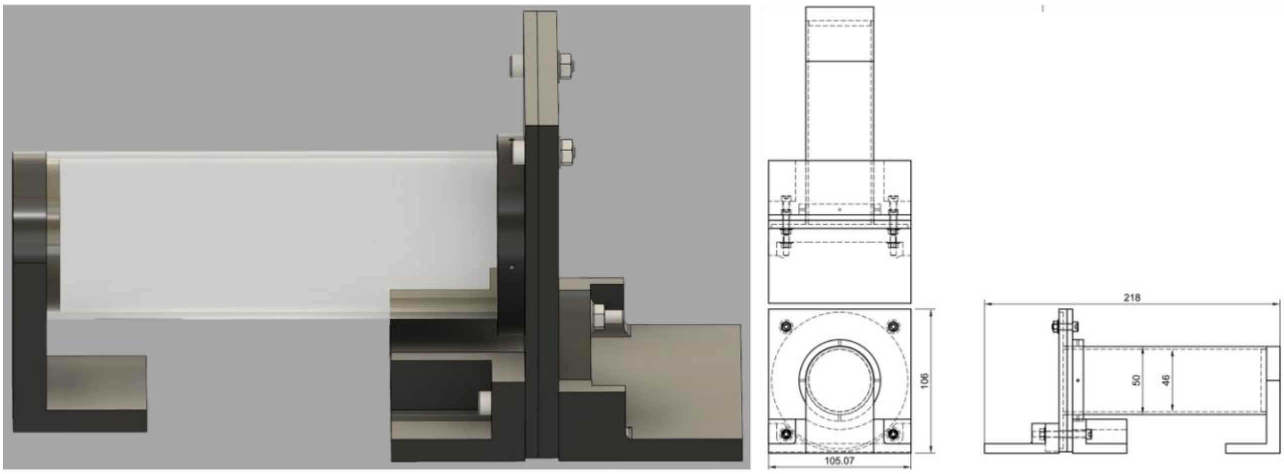

Figure 6. CAD-based rendering of the experimental equipment without the speaker (left) and corresponding technical drawing (all dimensions in mm) (right)

3.3. *Results*

Before the drop, striped patterns appeared in a planar configuration as shown in Fig. 7. During the microgravity phase, these patterns lifted and became three-dimensional (Fig. 8). However, the polystyrene particles exhibited irregular motion, resulting in less distinct patterns compared to ground experiments.

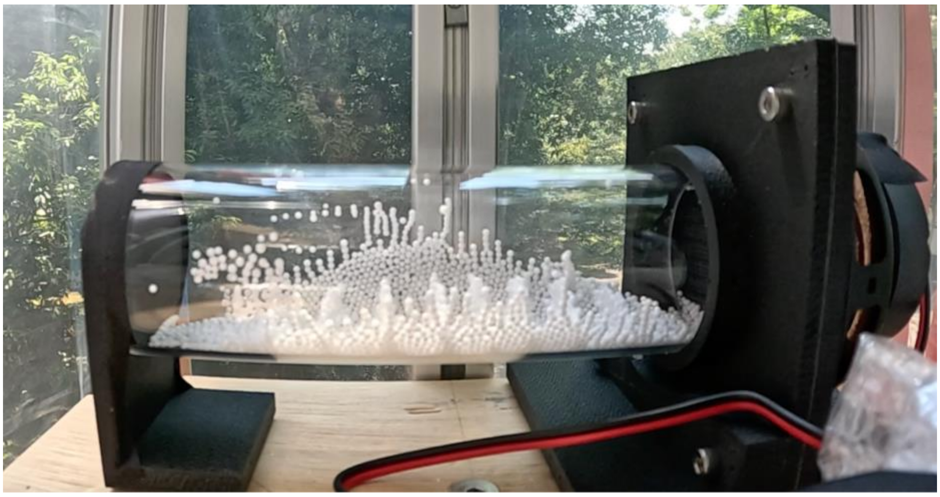

Figure 7. Kundt's experimental equipment immediately before the drop

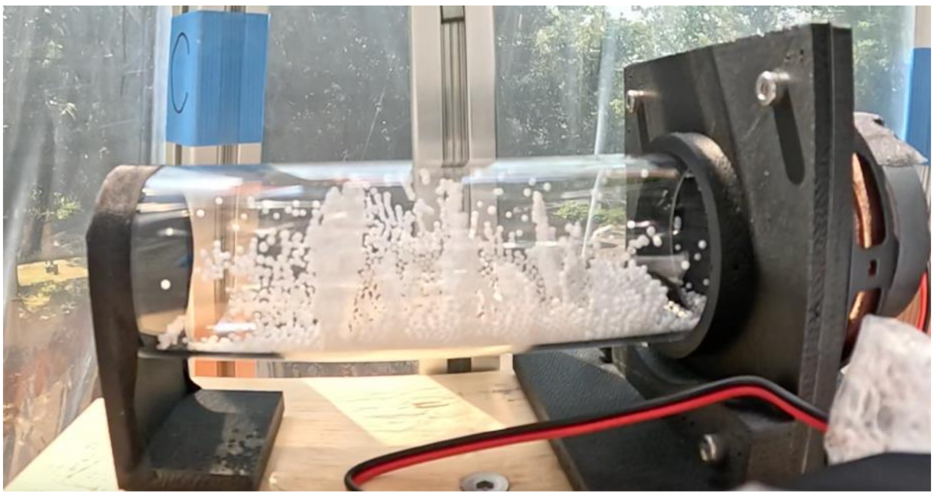

Figure 8. Kundt's experimental equipment during the drop

4. Discussion

4.1. *Effects of Equipment Improvements*

The improvements from TGμ-DS1 to TGμ-DS2 resulted in a significant enhancement of microgravity environment quality. In particular, expanding the clearance between the drag shield and inner capsule from 25 mm to 50 mm prevented contact between the two capsules during free fall. As shown in Fig. 4, a stable microgravity environment was achieved after the improvements, regardless of the presence or absence of experimental equipment.

As a result of these improvements, TGμ-DS2 enabled the realization of a stable microgravity environment at the 10^{-3}–10^{-2} g level for approximately 1.0 s. This performance represents a comparatively high standard for equipment that can be installed in domestic educational institutions and provides sufficient quality for basic microgravity experiments.

4.2. *Cost Performance*

The construction cost of this apparatus was approximately JPY 200,000, enabling microgravity experiments at less than 1/100 of the cost compared to ISS experiments (tens of millions of JPY) or aircraft parabolic flights (several million JPY). This cost reduction makes it possible to conduct microgravity experiments, which were previously limited to select research institutions, at high schools and universities nationwide. This has the potential to significantly expand the foundation of microgravity science research and contribute to nurturing the next generation of space science researchers.

4.3. *Three-Dimensional Visualization Experiment of Acoustic Standing Waves*

In Kundt's tube experiments conducted under microgravity conditions, the three-dimensional structure of acoustic standing waves was clearly captured. As shown in Fig. 8, particles were distributed three-dimensionally throughout the tube, enabling direct observation of the spatial structure of the sound pressure distribution. This represents an important achievement in extending observations from the two-dimensional plane limitations under gravity to three-dimensional space.

However, irregular behavior was observed in the polystyrene particles, and the stripe patterns became less distinct compared to ground experiments. This is likely because the sound pressure settings optimized for ground experiments were excessive for the microgravity environment. In the absence of gravity, the force required to maintain particles at the pressure antinodes decreases, suggesting that using the same sound pressure as on the ground results in excessive particle vibration.

4.4. *Future Prospects*

Several improvements and developments are required for future acoustic experiments.

First, it is necessary to re-optimize the sound pressure suitable for microgravity environments to achieve stable particle positioning. It is also important to explore optimal experimental conditions by conducting experiments with particles of different diameters.

Furthermore, experiments involving higher-order modes and frequency bands beyond the current fundamental frequency of 996 Hz will allow for a more comprehensive understanding of acoustic phenomena.

For experimental evaluation, we plan to establish quantitative methods for assessing particle distributions using image analysis techniques and to advance theoretical validation by comparing the obtained data with numerical simulations.

5. Conclusion

In this research, the drag-shield-type drop experiment apparatus TGμ-DS2 was developed, achieving a high-quality microgravity environment at low cost. By expanding the drag shield, TGμ-DS2 stably achieved a microgravity environment in the range of 10^{-3}–10^{-2} g for approximately 1.0 s. The construction cost was low at approximately JPY 200,000, enabling experiments at less than 1/100 of the cost compared to conventional microgravity experimental methods.

In the three-dimensional visualization experiment of acoustic standing waves, clear images of the spatial structure of sound pressure distribution under microgravity conditions were captured. New insights were also gained regarding the necessity of sound pressure settings appropriate for microgravity environments. Going forward, this will be established as a new experimental method in acoustic physics through experiments at multiple frequencies and quantitative evaluation using image analysis.

The development of TGμ-DS2 makes it possible to conduct microgravity experiments, previously limited to select institutions, in a wide range of facilities, including schools, research centers, companies, and science museums. This brings innovation to space experiment education and significantly contributes to expanding the foundation of microgravity science research. Furthermore, it holds important significance as a fundamental research platform for future space habitation.

TGμ-DS2 is expected to contribute to the development of microgravity science as an apparatus that provides a high-quality microgravity experimental environment despite its low cost.

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7. References

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