Journal of Asian Concrete Federation

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Detachment Diagnosis for the External Tile Finishing Wall Using Spatula Mounted on Wall-contact type UAV

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A B S T R A C T

In Japan, the Building Standards Act mandates periodic inspections of external tile walls. Conventional hammering tests require scaffolding, resulting in high cost and labor intensity. As an efficient and safer alternative, drone-assisted hammering inspections have been studied. Previous research identified lightweight stainless-steel spatulas as effective for detecting tile detachment; however, the optimal dimensions for acoustic diagnosis and their applicability to wall-contact drones remain unclear.This study aims to identify the most suitable spatula dimensions for acoustic detection of tile detachment and evaluate their performance when mounted on a drone. Experiments were conducted on tile wall specimens with artificial detachment zones. Spatulas of varying lengths and widths were slid over tile joints under constant contact pressure to simulate tapping and generate repetitive impact sounds. The recorded sounds were analyzed using Fast Fourier Transform (FFT) to calculate average sound pressure levels in two frequency bands, Δf_1 (1000–2000 Hz) and Δf_2 (4000–5000 Hz).Results indicated that a 30 mm × 15 mm spatula produced the largest difference in sound pressure level (up to 16 dB) between normal and detached areas, and 5 dB when mounted on a drone. These findings demonstrate the feasibility of drone-based acoustic detachment diagnosis using optimally dimensioned spatulas.

Keywords: Spatula, Drone, Hammering Test, Fast Fourier Transform, Frequency

1. Introduction

In Japan, the periodic inspection of external tile finishing walls is mandated for building owners and related parties under Article 12 of the Building Standards Act. Hammering inspections require the installation of scaffolding or gondolas, and skilled technicians with specialized knowledge and experience are necessary to perform them. As a result, such inspections impose considerable cost and time burdens on building owners. Therefore, it is essential that inspections of external tile finishing walls be conducted at low cost, quickly, and accurately. To address these challenges, the authors proposed performing hammering inspections using an Unmanned Aerial Vehicle (hereinafter referred to as a "UAV"). This approach enables efficient inspections without the need for scaffolding or gondolas.

On the other hand, UAVs must minimize their payload to ensure sufficient flight time and stability. According to previous research [1], tile detachment can be detected using a lightweight spatula instead of a test hammer, and stainless-steel spatulas were found to be the most effective for detecting detachment. This method involves measuring the sound pressure generated while sliding a spatula across the tile surface to identify defective areas. However, the optimal dimensions of the spatula have not yet been clarified.

In this study, the optimal dimensions of a stainless-steel spatula and its applicability for detecting tile detachment when mounted on a UAV are investigated through the following three steps. The experiments target widely used 50 mm × 100 mm cement-mortar-bonded exterior tiles, in which square artificial detachment areas of 200 mm × 200 mm and 300 mm × 300 mm are introduced as representative detachment sizes.

1)Various spatula lengths are tested by sliding them over the tile surface to determine the optimal length for detachment detection.

2)Using the optimal length obtained in step 1), the spatula

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DOI http://dx.doi.org/10.18702/acf.2026.12.2.1

Received: 30-Oct-2025; Revised: 21-Feb-2026; Accepted: 23-Feb-2026; Published online: 27-April-2026

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width is varied to determine the optimal width for detachment detection.

3)The spatula with the determined dimensions is mounted on a UAV, and tile detachment detection is conducted.

Although this study focuses on specific tile and detachment sizes, the proposed methodology provides a fundamental basis for extending UAV-based detachment detection to other tile configurations and detachment sizes in future research.

2. Experimental Apparatus and Specimens

2.1 Spatula

Figure 1 shows the spatulas with different length and width configurations used in this study. The material of the spatula is stainless-steel (JIS SUS430, equivalent to AISI Type 430), with a density of 7.7 g/cm^3 and an elastic modulus of 215 GPa. The spatula length (20-60 mm, in 10 mm increments) and width (5-15 mm, in 5 mm increments) were varied as experimental parameters. To prevent tile surface damage during sliding, the tip of the spatula is chamfered.

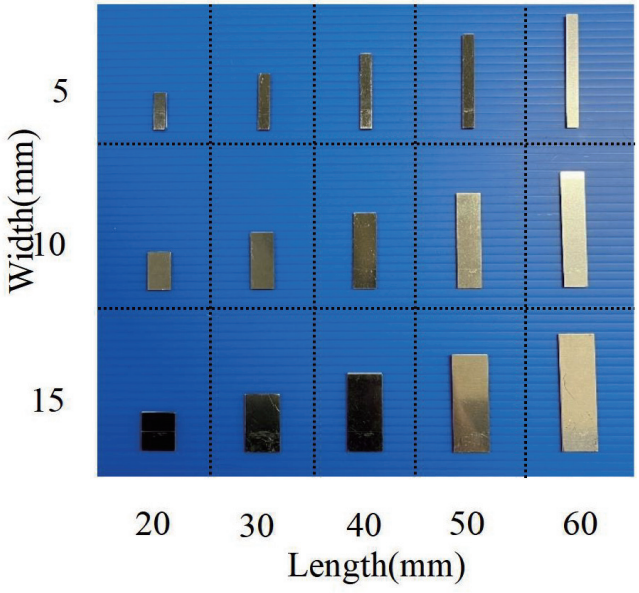


Fig. 1 Spatulas with different length and width configurations

In this study, a general-purpose UAV that is relatively inexpensive and easy to operate is used. The UAV is equipped with four front-mounted wheels that enable stable vertical movement after contacting the wall surface (hereinafter referred to as a "wall-contact-type UAV"). Figure 2 shows the wall-contact-type UAV used in the experiment. The UAV is equipped with a spatula, a microphone, and a small camera. When mounted on the UAV, the distance between the spatula tip and the microphone was reduced to 50 mm to minimize the influence of propeller-generated noise and to more clearly capture the impact sound.

2.3 Pseudo-void Specimens

Pseudo-void specimens were prepared with reference to previous research [2]. A 1 mm-thick polyethylene foam sheet was inserted at the interface between the concrete and the underlayment mortar as a simulated void to reproduce the detachment condition. Figure 3 shows the pseudo-void specimen, Table 1 lists the materials and specifications, and Figure 4 shows the cross-section of the specimen. The specimens were tested more than three years after fabrication, by which time sufficient curing had occurred.

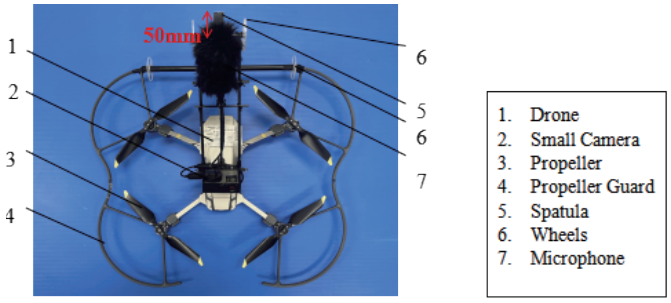


Fig. 2 Wall-contact-type UAV

3. Experiment on the Effect of Spatula Dimensions

3.1 Experimental Method

The spatula was clamped 10 mm from its tip using pliers. It was then slid over both the normal and detached areas of the pseudo-void specimen, and the sounds generated during sliding over the tile joints were recorded. Figure 5 shows the experimental setup, and Figure 6 shows the positions of the pseudo-void and the tiles where the spatula was slid over the



Fig. 3 Pseudo-void specimen

joints. Since sound is generated at the boundary between the tiles and the joint during sliding, the spatula was slid across two adjacent tiles over the joint.

The microphone was placed 150 mm away from the wall surface. The recorded sounds were analyzed using Fast Fourier Transform (FFT) with 256 analysis points and a Hanning window function.

Table 1 Material specification and composition of pseudo-void specimen

Material	Specification
Concrete	1150 mm×6300 mm×215 mm
Water Absorption Regulator	Ethylene Vinyl Acetate Emulsion
Pseudo-void	Polyethylene Foam Sheet Forming Ratio: 30 times、Thickness: 1 mm Area: 300 mm square
Underlayment Mortar	Ordinary Mortar (Cement : Sand = 1 : 3) Thickness: 10mm
Adhesive Mortar	Pre-mixed Mortar for Tiling
Tile	For Mortar Application, 45 mm×95 mm×7 mm
Joint Mortar	Pre-mixed Mortar for joint, Width: 5 mm

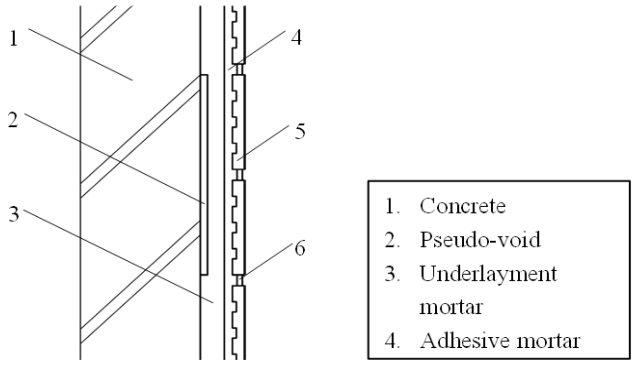


Fig.4 Cross-section of pseudo-void specimen

Each experimental condition was repeated 10 times under the same measurement settings. The repeated trials showed consistent spectral characteristics in the frequency–sound pressure relationship, and the distinction between normal and detached areas was consistently observed. Therefore, representative results are presented in the following sections for clarity.

3.1.1 Measurement with Different Spatula Lengths

The spatula width was fixed at 15 mm, and the length was varied from 20 to 60 mm in 10 mm increments.

3.1.2 Measurement with Different Spatula Widths

Using the optimal length obtained in Section 3.1.1, the spatula width was varied from 5 to 15 mm in increments of 5 mm.

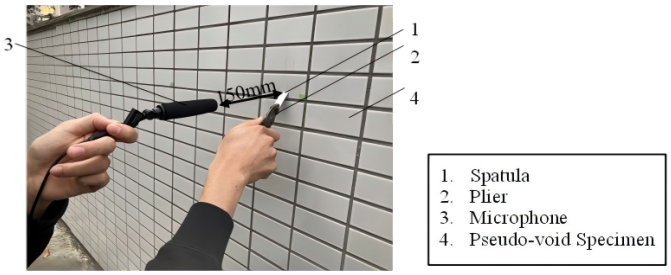


Fig. 5 Experimental setup

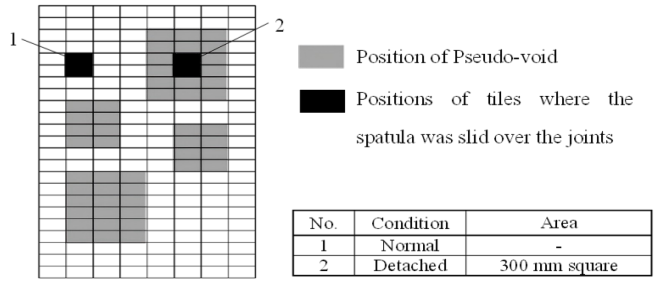


Fig. 6 Position of pseudo-void and tiles where the spatula was slid over the joints

3.2 Results and Discussion

Two frequency spans were defined: Δf_1 = 1000-2000 Hz and Δf_2 = 4000-5000 Hz. The presence of detachment was determined from the difference (L_2 - L_1) [dB] between the average sound pressure level L_1 in Δf_1 and L_2 in Δf_2 [3].

The frequency range below 1000 Hz is dominated by aerodynamic noise generated by the UAV propellers. In contrast, within the Δf_1 band, the sound pressure level in detached areas becomes significantly higher than that in normal areas. To compensate for overall fluctuations in sound pressure level caused by variations in impact force, the Δf_2 band is used as a reference. By taking the difference between the average sound pressure levels in Δf_2 and Δf_1, it becomes possible to account for global amplitude variations and achieve stable discrimination even in the presence of aerodynamic noise.

3.2.1 Effect of Spatula Length

Figures 7-11 show the relationships between sound pressure level and frequency for spatulas with lengths of 20-60 mm and width of 15 mm. Table 2 shows the average sound pressure levels in each frequency span and their differences. The figures present the sounds generated by sliding over the tile joints, with the maximum sound pressure level for each case.

From Figures 7 and 8, a large difference was observed

between the waveforms of the normal and detached areas near 0-5000 Hz. In Figure 9, the difference appeared around 0-3000 Hz, while in Figures 10 and 11, it appeared around 0-2000 Hz. As the spatula length increased, the difference between the waveforms of the normal and detached areas became less noticeable.

From Figure 7 and Table 2, when the spatula length was 20 mm, the difference in average sound pressure level between normal and detached areas was only 7 dB, making detachment detection difficult. This is considered to be due to the smaller sound components below 6000 Hz in the normal area, resulting in a small level difference.

From Figure 8 and Table 2, when the spatula length was 30 mm, the difference was 16 dB, allowing clear identification of detachment.

In Figures 9-11, except around 0-3000 Hz, there was no significant difference between the normal and detached areas. During the experiment, the sounds generated by sliding over the tile joints were noticeably different between the 20-30 mm and 40-60 mm spatulas. The spatula can be mechanically approximated as a cantilever beam fixed at one end. As the length increases, bending stiffness decreases and flexibility increases, making longer spatulas (40–60 mm) more prone to vibrate when impacted during sliding. These structural vibrations generate additional sound in the 0–4000 Hz range, which can overlap with the tile impact signal and act as measurement noise.

Therefore, within the scope of this study, a spatula length of 30 mm, at which the difference in average sound pressure level between the normal and detached areas reached 16 dB, is considered optimal.

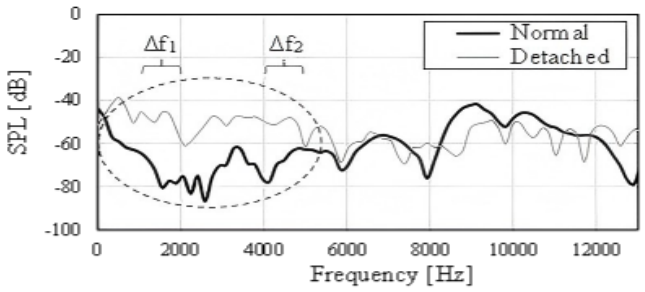


Fig. 7 Relationship between sound pressure level and frequency
(spatula length = 20 mm, width = 15 mm)

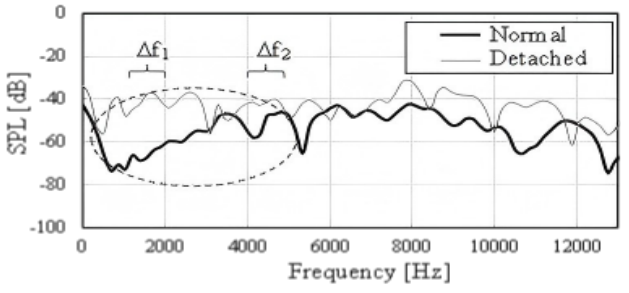


Fig. 8 Relationship between sound pressure level and frequency
(spatula length = 30 mm, width = 15 mm)

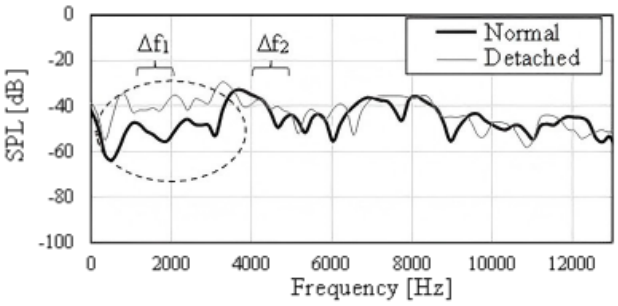


Fig. 9 Relationship between sound pressure level and frequency
(spatula length = 40 mm, width = 15 mm)

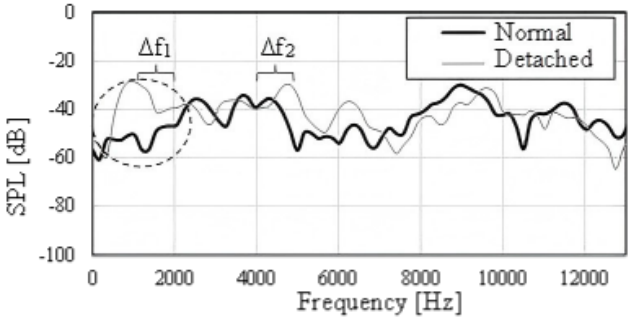


Fig. 10 Relationship between sound pressure level and frequency
(spatula length = 50 mm, width = 15 mm)

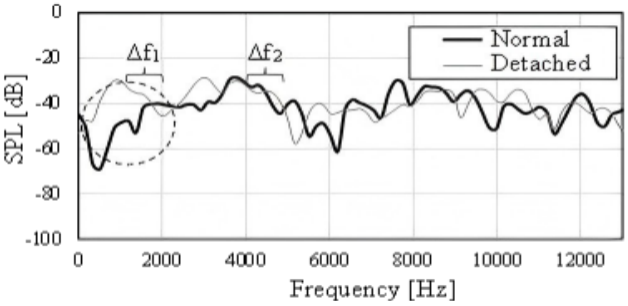


Fig. 11 Relationship between sound pressure level and frequency
(spatula length = 60 mm, width = 15 mm)

3.2.2 Effect of Spatula Width

Based on Section 3.2.1, the spatula length was fixed at 30 mm. Figures 12 and 13 show the relationships between sound pressure level and frequency for spatulas with widths of 5 mm and 10 mm, respectively, and Table 3 shows the average sound pressure levels and their differences. Each figure presents the sounds generated by sliding over the tile joints, corresponding to the maximum sound pressure level in each case.

From Figures 8, 12, and 13, no significant differences were observed in the spectral characteristics due to spatula width. However, Table 3 indicates that, except for the normal area with a width of 10 mm, the average sound pressure levels L_1

and L_2 increased as the spatula width increased. Yoshimoto et al. [4] conducted experiments in which water droplets were dropped onto stainless-steel plates and found that the sound pressure level of the impact noise increased with droplet diameter. As the droplet diameter increased, the contact area at impact also increased. Similarly, as the spatula width increases, the contact area between the spatula and the tile during sliding over the tile joints becomes larger, producing more sound and resulting in higher sound pressure levels.

Table 2 Average sound pressure levels in each frequency span and their differences for different spatula lengths

Spatula length [mm]	Condition	L_1[dB]	L_2[dB]	L_2-L_1[dB]
20	Normal	-74	-69	+5
	Detached	-50	-52	-2
30	Normal	-66	-51	+15
	Detached	-42	-43	-1
40	Normal	-52	-42	+10
	Detached	-40	-40	0
50	Normal	-51	-42	+9
	Detached	-36	-35	+1
60	Normal	-45	-37	+8
	Detached	-38	-37	+1

Therefore, within the scope of this study, a spatula width of 15 mm, which provides a larger contact area, is considered optimal.

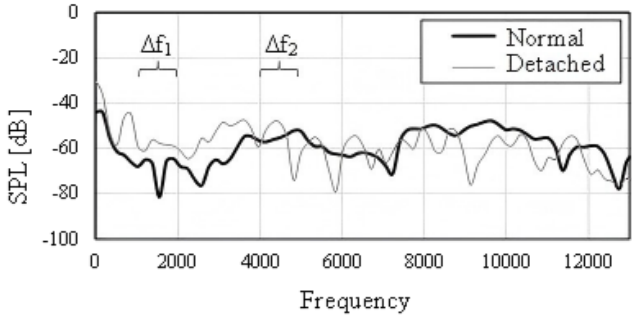


Fig. 12 Relationship between sound pressure level and frequency
(spatula length = 30 mm, width = 5 mm)

4. Experiment Using the Wall-contact-type UAV with Mounted Spatula

4.1 Experimental Method

The wall-contact-type UAV was used to detect the presence of detachment in the pseudo-void specimen. Based on the results of Chapter 3, a spatula with a length of 30 mm and a width of 15 mm was mounted on the UAV. The same sliding positions over the tile joints as in Chapter 3 were used, and the resulting sliding sounds were recorded. Figure 14 shows the experimental setup using the wall-contact-type UAV.

To minimize the influence of propeller noise, a super-directional microphone was used, and the microphone was pointed directly toward the spatula. FFT analysis was performed using PC software with 256 analysis points and a Hanning window function.

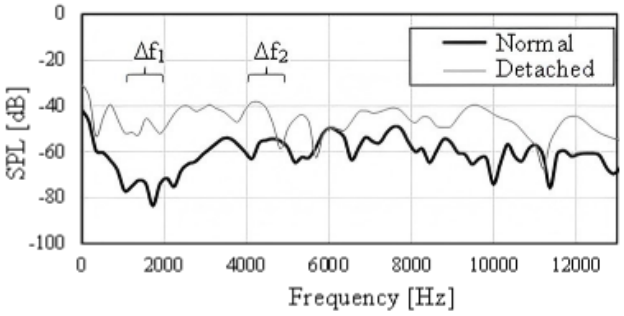


Fig. 13 Relationship between sound pressure level and frequency
(spatula length = 30 mm, width = 10 mm)

Table 3 Average sound pressure levels in each frequency span and their differences for different spatula widths

Spatula Width [mm]	Condition	L_1[dB]	L_2[dB]	L_2-L_1[dB]
5	Normal	-68	-55	+13
	Detached	-59	-57	+2
10	Normal	-75	-57	+18
	Detached	-50	-45	+5
15	Normal	-66	-51	+15
	Detached	-42	-43	-1

4.2 Results and Discussion

Figure 15 shows the relationship between sound pressure level and frequency for the sounds generated by sliding over the tile joints in the normal and detached areas, obtained using the wall-contact-type UAV equipped with a 30 mm × 15 mm spatula. Table 4 shows the average sound pressure levels in each frequency span and their differences. Each figure presents the sliding sound with the maximum sound pressure level.

From Figure 15, no significant difference in waveform was observed between the normal and detached areas. However, Table 4 shows that the difference in average sound pressure

level between the two areas was 5 dB. In the detached area, the sound pressure levels in Δf1 and Δf2 were higher than those of the propeller noise, providing sufficient data on the sounds generated by sliding over the tile joints. In contrast, for the normal area, the average sound pressure level L_1 [dB] did not decrease as much as when the spatula was manually operated with pliers, resulting in a smaller difference of only 5 dB between L_1 and L_2.

It has been reported [5] that propeller noise contains many frequency components below 1000 Hz. In the detached area, since the sound pressure level above 1000 Hz exceeded that of the propeller noise, its influence was relatively small. However, in the normal area, even in the range of 1000-2000 Hz, the sound was masked by propeller noise, indicating a strong influence.

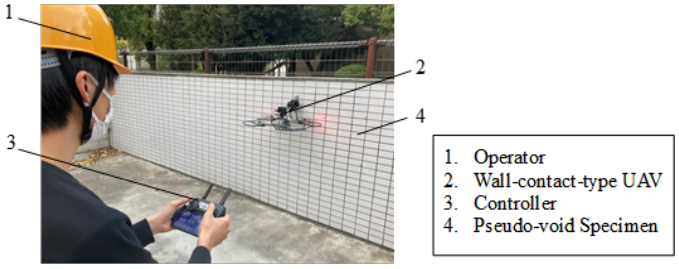


Fig. 14 Experimental setup using the wall-contact-type UAV

Therefore, to improve the accuracy of detachment detection using a wall-contact-type UAV, it is necessary to further reduce the effect of propeller noise in the normal area, which remains a subject for future study. Future work should address this issue from three perspectives.

First, structural improvements, including optimization of propeller blade geometry and reduction of tip vortices, should be investigated to suppress aerodynamic noise generation. Second, control-based approaches, such as rotational speed optimization and adaptive thrust control during impact, may further mitigate noise fluctuations. Third, machine-learning-based noise reduction techniques, including data-driven noise cancellation and filtering methods, should be explored to reduce the influence of propeller noise and enhance the reliability of detachment detection.

Through these improvements, a more stable and practical UAV-based detachment diagnosis system can be realized.

5. Conclusions

1) As the spatula length increases, the difference in waveform between the normal and detached areas becomes smaller. This suggests that when the spatula length is large, vibrations caused by the impact generated during sliding over the tile joints produce sound components in the range of 0-4000 Hz.

2) Increasing the spatula width enlarges the contact area between the spatula and the tile during sliding over the tile joints, which facilitates sound generation and increases the sound pressure level.

3) A spatula with a length of 30 mm and a width of 15 mm is optimal for identifying the presence of detachment.

4) When a wall-contact-type UAV equipped with a 30 mm × 15 mm spatula was used, the difference in average sound pressure level between the normal and detached areas was 5 dB. For accurate detection using the wall-contact-type UAV, it is necessary to minimize the influence of propeller noise, especially in the normal area, which remains an issue for future research. Future work will focus on aerodynamic design improvements, control optimization, and machine-learning-based noise suppression to enhance the practicality of the proposed method.

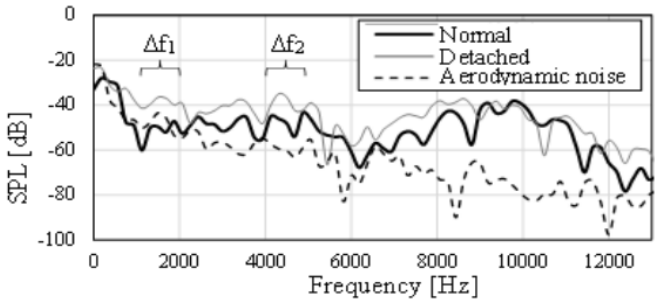


Fig. 15 Relationship between sound pressure level and frequency
(Wall-contact-type UAV)

Table 4 Average sound pressure levels in each frequency span and their differences (Wall-contact-type UAV)

	Condition	L_1[dB]	L_2[dB]	L_2-L_1[dB]
UAV	Normal	-52	-47	+5
	Detached	-39	-39	+0

CRediT authorship contribution statement:

Yosuke Ito: Conceptualization, Methodology, Writing - original draft

Daiki Tanaka: Conceptualization, Methodology, Writing - review & editing

Shinji Kawabe: Conceptualization, Methodology, Supervision

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by the Japan Science and

Technology Agency (JST), Support for Pioneering Research Initiated by the Next Generation, Grant Number JPMJSP2112. The authors would like to express their sincere gratitude to H. Nagai of Nagoya Institute of Technology (at that time), M. Yamada of Nagoya Institute of Technology, M. Watanabe of M&T Co., Ltd., and K. Yamasaki and Y. Kuriaki of LIXIL Corporation (at that time) for their valuable cooperation, technical advice, and generous assistance throughout this research.

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