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Efficiency Improvement of Outer Wall Inspection by Noncontact Acoustic Inspection Method using Sound Source Mounted Type UAV

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***Abstract*—We are verifying the applicability to the inspection of tile outer walls using sound source mounted type UAV (Unmanned Aerial Vehicle). In the previous study, it was clarified that defects can be detected even with a small planar sound source that can be mounted on a UAV. However, at a flight altitude of around 2m, the aircraft was found to be slightly unstable due to the wind generated by the large UAV itself. Therefore, this time, the flight altitude was set to about 4m by arranging the outer wall tile specimen itself on another concrete specimen. It was examined whether or not the defect could be detected by acoustic irradiation from UAV in flight. The effectiveness of the proposed method was confirmed from the verification experiment results.**

Keywords— Noncontact acoustic inspection, UAV, Acoustic irradiation induced vibration, Laser Doppler vibrometer

I. INTRODUCTION

Old concrete structures and buildings need to be regularly inspected because of the risk of falling concrete pieces and peeling off outer wall tiles. Generally, a hammering inspection is used for inspection, but frequent inspection is difficult due to the large cost of temporary scaffolding. Therefore, the development of a method that enables long-distance and noncontact inspection is required. Infrared method using an infrared camera [1] and laser remote sensing methods using a pulsed laser [2] have already been proposed as methods that enable inspection at a long distance. However, the former has a problem that, under a tunnel or a bridge where the temperature change is small, heating by a heater or the like is required at the time of detection, and in general, it is easily affected by a temperature change caused by sunlight. In the latter, a safety problem due to the use of a plurality of high-power lasers is pointed out. Therefore, we proposed a noncontact acoustic inspection (NCAI) method using acoustic irradiation induced vibration and a laser Doppler vibrometer (LDV), and the simulated cavity defect embedded in the concrete specimen is 5m or more. It was clarified that it can be detected from a distance [3]. In order to improve practical defect detection performance, a single tone burst wave [4], vibration energy ratio [5], and a defect detection algorithm [6,7] using spectral entropy have been devised. In addition, multitone burst waves [8] that enable high speed measurement and spatial spectral entropy [9,10] have been devised to detect the resonance of the defect and the head resonance of the LDV separately. Verification experiments were carried out on actual railway tunnels, viaducts over 30 m[11], and shotcrete with rough surfaces[12,13], and it became clear that defect detection almost equivalent to hammer inspection is possible even at long distances and noncontact. On the other hand, the problem of this method is the angle dependency of the sound source and the environmental noise. However, if the sound source itself is mounted on the unmanned aerial vehicle (UAV) and the sound wave can be irradiated from the vicinity of the measurement object, it is expected that these problems themselves will be solved because a commercially available small sound source can be measured. Therefore, in order to solve the problems of the NCAI method and widen the scope of application, we examined the outer wall inspection by the NCAI method using a UAV equipped with a sound source[14,15].

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II. NONCONTACT ACOUSTIC INSPECTION METHOD

A. Basic Principle

Fig. 1 shows the basic setup for the noncontact acoustic inspection (NCAI) method. The measurement surface is excited

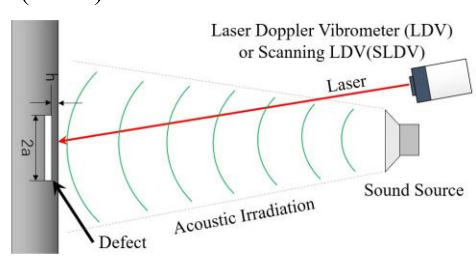

Fig.1. Basic setup for noncontact acoustic inspection method.

by sound waves emitted from a sound source, and the vibration velocity distribution is measured using an LDV or a scanning vibrometer (SLDV). If a defect such as a horizontal crack or void exists in the vicinity of the surface to be measured, the bending rigidity is lower on the defective portion than on the healthy part. Therefore, flexural vibration can be generated even with a weak force such as sound waves. For this reason, in this method, by generating the same flexural vibration as that in the hammer inspection by acoustic irradiation induced vibration, it is possible to detect a cavity and a separation defect existing near the surface of the measurement target. For simplicity, the natural frequency (resonance frequency) f_r can be expressed by equation (1) when the peeled part is approximated to a simply supported disk [16].

$$f_r = \frac{4.98}{2\pi a^2}\sqrt{\frac{Eh^2}{12\rho(1-\upsilon^2)}} \tag{1}$$

Where h is the depth from the measurement surface to the defect (m), a is the radius of the disk (m), E is the Young's modulus (Pa), v is the Poisson's ratio, and ρ is the density (kg / m^3).

B. Emission Waveform

Usually, the flexural resonance frequency of the defect is unknown. For this reason, the emission waveform needs to include the corresponding frequency band in order to find the flexural resonance frequency of the defective part. Therefore, in this method, a tone burst wave that can cover a necessary frequency band and can generate an excitation force necessary to generate resonance vibration is used as a emission waveform. In this measurement, a multitone burst (MTNB) wave was used to realize high-speed measurement as shown in Fig.2.

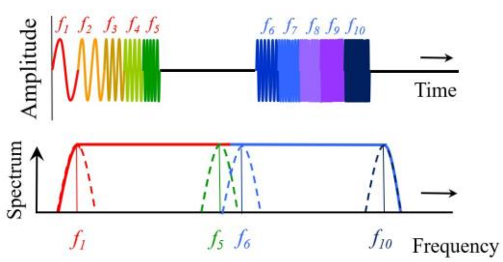

Fig.2. Conceptual diagram of MTNB waveform.

C. Vibration Energy

Defects existing in the actual structure often have a complicated shape and may have a plurality of resonance peaks. In such a case, it is not possible to clarify the defect scale by imaging only a single resonance frequency. Therefore, the vibration energy ratio (VER) is defined as shown in Eq. (2), assuming that the sum of the power spectrum of the vibration velocity in a certain frequency range is a value corresponding to the vibration energy.

$$[VER]_{dB} = 10\log_{10}\frac{\int_{f_1}^{f_2}(PSD_{defect})df}{\int_{f_1}^{f_2}(PSD_{health})df} \tag{2}$$

Here, PSD_{defect} and PSD_{health} are power spectral density (PSD) of the defective part and the healthy part, and f_1 and f_2 are the lower limit and the upper limit frequency. In an actual structure, there may be some variation in the healthy part, but here, the lowest value of vibration energy in the measured healthy part is calculated as PSD_{health}.

III. Sound Source Mounted Type UAV and Tiled Outer Wall Specimen

A. Sound Source Mounted Type UAV

Fig. 3 shows an external view of the UAV with sound source in flight. A plane sound source (FPS Corp., 1030M3F1R), a laser pointer for aiming, a laser range finder, and an FM receiver are installed at the bottom of the base drone (DJI Corp., Matrice 600 Pro). The UAV itself weighs about 10 kg and can fly for about 20 minutes with a sound source and an amplifier. Moreover, the waveform of the acoustic irradiation induced vibration can be transmitted from the FM transmitter, and can be synchronized with the measurement on the LDV side.

Fig.3. Photograph of the sound source mounted type UAV in flight.

B. Tiled Outer Wall Specimen

A tiled outer wall specimen (2 × 1.6 × 0.2 m^3) was fabricated for a verification experiment of the outer wall inspection using a drone. Fig.4 shows a layout of the simulated crack defects embedded in the specimen. As a simulated crack defect, a 0.5 mm thick styrene sheet and a 0.5 mm thick foam sheet were used. The defect shape is square, and there are four types of defect sizes: 50 mm^2, 100 mm^2, 150 mm^2, and 200 mm^2. Each sheet is placed on reinforced concrete. The styrene sheet is affixed to the surrounding four sides, and the foam sheet is affixed to the entire surface with about 0.5 mm thick tape. The size of one tile is about 45 × 95 × 7 mm^3, and the thickness of the adhesive mortar is about 3 mm. Therefore, the styrene sheet is embedded at a depth of about 9.5 mm from the tile surface,

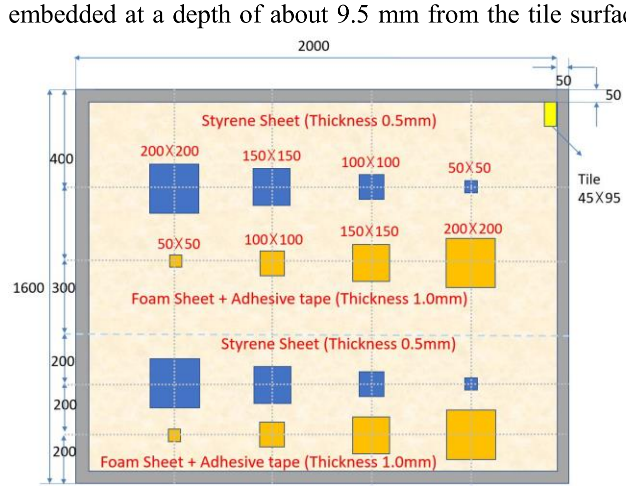

Fig.4. Arrangement of the simulated crack of the outer wall specimen.

and the foam sheet is embedded at a depth of about 9 mm from the tile surface. However, for a 50 mm^2 defect, it was revealed in a previous experiment that the flexural resonance frequency was 10 kHz or higher.

IV. Acoustic Irradiation Experiment from UAV in Flight

A. *Directivity of the Flat Spekaer Mounted on UAV*

When the UAV actually flies, it is expected that the UAV itself will sway under the influence of natural winds. However, in the case of acoustic irradiation induced vibration, it is predicted that the defect detection itself is possible if the defect position is within the directivity range of the sound source even if the sound source and the defect position do not face each other. The directivity angle (the angle at which the sound pressure is reduced by 6 dB relative to the sound source center sound pressure) of the flat speaker installed in the UAV is about 30 degrees at 4 kHz. Therefore, if there is a distance of about 3 m from the sound source, it is possible to irradiate sound waves with a frequency of 4 kHz or less on almost the entire surface of the tiled outer wall specimen. In order to confirm this, the sound pressure on the front surface of the specimen was actually measured using a tone burst wave of 0.5 to 4 kHz. The experimental setup and sound pressure distribution measurement results are shown in Fig. 5 and Fig. 6, respectively. From these figures, it can be seen that in the horizontal direction, a sound wave of 80 dB (time average value) or more is applied to almost the entire surface of the specimen even at a distance of 4 m. From this, it can be said that if the sound wave can be irradiated to the center of the specimen, this specimen can measure almost the entire surface.

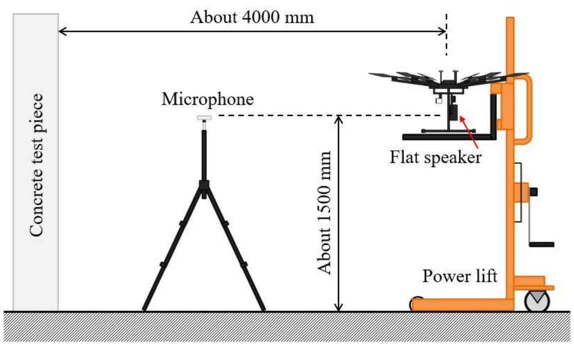

Fig.5. Experimental setup for sound pressure distribution.

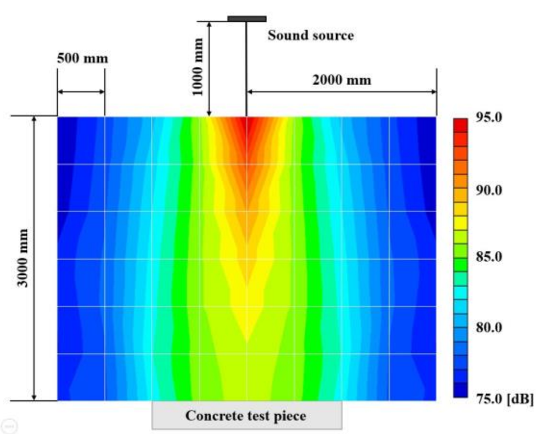

Fig.6. Sound pressure distribution of the flat speaker.

B. *Experimental Setup*

From the results of last year's experiment, it became clear that large UAVs show unstable behavior due to the wind generated by the propellers of UAVs at low altitudes of about 2 m. Therefore, this time, an experiment was conducted in which the flight altitude of the UAV was raised by suspending the outer wall specimen itself from another concrete specimen (height 3 m) using a large crane vehicle as shown in Fig.7. The sound source mounted type UAV was operated so as to face the central part of the specimen, and the distance to the tile surface was in the range of 3 to 5 m. The reason why the distance is not constant is that the UAV itself sways under the influence of natural wind. Scanning LDV (Polytec corp., PSV-500 Xtra) measured vibrations at a distance of approximately 11.2 m diagonally upward. The waveform used for acoustic irradiation induced vibration is a MTNB wave [8] (frequency range 0.5 to 4 kHz, pulse length 3 ms (interval frequency 100 Hz), overall waveform length 60 ms). The sound pressure is set to about 90 dB (maximum value of Z characteristics) at a distance of 5 m.

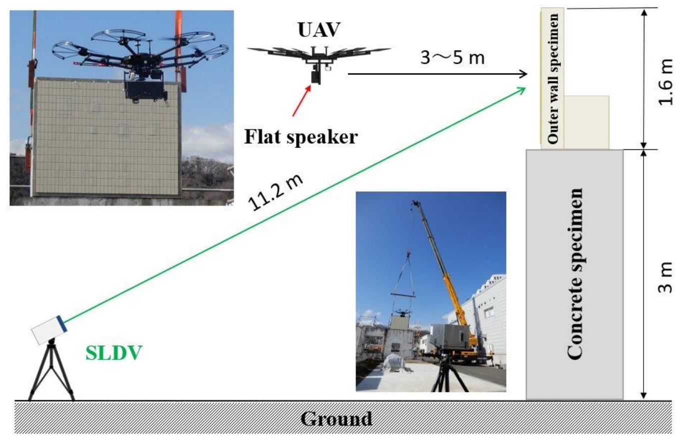

Fig.7. Experimental setup for acoustic irradiation induced vibration from UAV in flight.

C. *Experimental Result*

The size of the measurement area was about 1.4 × 1.7 m^2, and 525 points (length 21 × width 25 points) were measured at intervals of about 70 mm in length and width. Fig. 8 shows an example of vibration energy ratio distribution. The frequency range for calculating the vibration energy ratio was set to 0.9 to 4 kHz in accordance with the flexural resonance frequency of the simulated defect size of 100 to 200 mm^2 (Since the 50 mm^2 defect has a high deflection resonance frequency of 10 kHz or higher, it is excluded from measurement this time). Since averaging was not performed, the measurement time was approximately 137 seconds. From this figure, it can be seen that 200 mm^2 for the styrene sheet and 150 mm^2 and 200 mm^2 for the foam sheet are detected without any problem even if the UAV is swayed by natural wind. The 100 mm^2 and 150 mm^2 of styrene sheets and 100 mm^2 of foamed sheets that were detected in laboratory experiments last year have not been clearly detected. However, since this cause is presumed to be due to the swinging movement of the UAV itself, a time-frequency gate that takes into account the swinging range of the UAV was created. Fig.9 shows the vibration energy distribution when this signal processing is applied. From this figure, it became clear that all defects could be detected while reducing noise. Actually, here, vibration energy is used instead of vibration energy ratio. This is because the value of the extracted vibration velocity spectrum of 100 mm^2 is small, and if the ratio with the lowest vibration energy value of the entire measurement area is taken, the whole image becomes unclear.

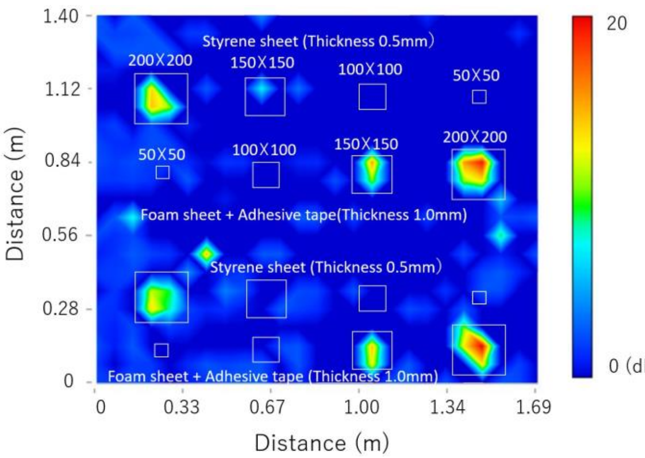

Fig.8 Vibration energy ratio distribution example (900-4000Hz).

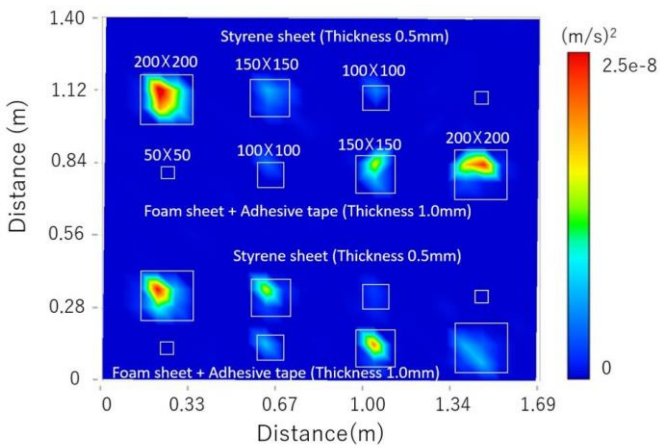

Fig.9 Vibration energy distribution example (500-4000Hz).

V. Conclusions

It became clear that the outer wall could be inspected by noncontact acoustic inspection method using acoustic irradiation induced vibration from UAV in flight. From the experimental results using the outer wall specimen, it was found that peeling defects of about 150 to 200 mm^2 can be detected without problems even if the UAV sways under the influence of natural wind. Furthermore, it became clear that a defect of about 100 mm^2 could be detected by applying signal processing considering the swinging range of UAV. In addition, since the distance between the sound source and the LDV can be increased, the influence of resonance of the LDV itself can be reduced, and high-speed measurement can be realized (approximately 0.26 seconds per point). Since the proposed method uses the same flexural resonance as the hammer inspection in principle, it can be used as an alternative method. In the future, we plan to improve the signal processing in consideration of the UAV swinging movement and to examine the practical application as a measurement system.

Acknowledgment

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