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Acoustical diagnosis of concrete crack depth based on its resonance

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ABSTRACT

Concrete is useful and indispensable material for the construction of modern buildings. However, it contracts after drying and causes cracks on its surface and in structure body. Moreover, long use period after construction make the crack deeper and wider. These bad states will cause peeling off and falling accidents. To prevent the accident, diagnose of the crack is necessary. Famous detection method for crack depth using ultrasonic wave was not used for inspection of concrete wall with wide area because there were faults with high cost and severe test condition as using grease. Therefore, authors tested other detection techniques for the crack depth, and then we found that the air column resonance being caused by a crack is similar to a wind instrument. It can be understood that the length of 1/4 of the wavelength of the first order resonance sound wave corresponds almost to the depth of air column with one end closed and the length of 1/2 of wavelength also to the depth with both ends open. We propose the method of non-destructive detecting crack depth based on the resonance phenomena. It has been understood that it would be able to detect for the width within 1mm on concrete wall in typical building by the spectral analysis peak at frequency of several hundred hertz. Under assumption of expanded use for special concrete constructions with very thick wall, we made some detection experiments by the addition. If depth increased, and width narrows, it became difficult to detect by the first order resonance as at frequency lower than one hundred hertz. Fortunately, higher order resonance phenomena, as at frequency several hundred hertz, were found and were able to be clearly caught in the experiments. It is possible to detect even by deep depth of about 1m with width of about 1 and 2mm. In the paper, principle and measurement ways of diagnosis based on the sound resonance are introduced, and the examination results are described.

INTRODUCTION

Concrete is useful and indispensable material for construction as many of modern buildings are constructed with it also in Japan and the world. When concrete structure dries and contracts after construction, many parts of the structure crack. Cracks may not cause problems still they are in narrow and shallow state.

However, after a long use period is passed, many cracks become deeper and wider and they may cause the decrease in structural strength. Possibility of dangerous accident falling the part of wall increases when deep and wide cracks on the outside wall of the concrete structure as street side building and road or train tunnel lead to the state of peeling off. It is necessary to detect the unsound part before such an accident happens and to repair.

There is the very famous ultrasonic wave method for the detection of fine crack on machine and pipe in many power plants and factories, and it may be very effective in these cases. For the using of grease in the actual inspects to contact the supersonic wave sending and receiving device to the surface of detection object, there are some problems concerning with cost and cleaning up of the grease after detections, with detection speed and with long total times for many inspecting works on the wide test area. Developments of low-cost, handy and easier detection methods are expected.

Authors have researched non-destructive diagnoses using sound and vibration techniques for some purposes. For example, authors studied methods to detect the part where crack is caused on concrete structure by using laser vibrometer and the method was able to find out the part clearly. Nevertheless, it is not able to recognize the crack depth that strongly influences on the soundness of concrete structure. Detection of the crack depth is very interesting subject for us. [1]

Authors had found out that sound resonance phenomenon occurred in thin groove like crack in the process of the development researches of some acoustical non-destructive diagnose. The resonance phenomenon seemed as same as called air column resonance in tube or pipe. So, authors were trying to realize the practical method for the estimation of depth of crack on the concrete structure. Authors propose the methods based on the sound resonance phenomenon. The principles of the methods and our experiment results are introduced in this paper.

PRINCIPLE OF DEPTH DETECTION

It is explained that the phenomenon called as “air column resonance” is caused in air tube, pipe and also small hole with certain depth on a wall even if it has not structure shape of the Helmholtz resonator. In addition, authors actually had caught similar resonance phenomena occurred in groove structure with two-dimensional extensions.

In the theory of air column resonance, it is known that two tube type structures of one end closed and both ends open have resonant frequencies depend on their geometrical size as shown in Figure 1. [2]

When L_e, c and n are the effective length of tube, the sound velocity in air and the natural number respectively, each resonant frequency f_{rn} is given from the following equations of (1) and (2),

$$f_{rn} = \left(\frac{n}{2} - \frac{1}{4}\right)\frac{c}{l_e}, \tag{1}$$

$$f_{rn} = \left(\frac{n}{2}\right)\frac{c}{l_e}. \tag{2}$$

Equation (1) or equation (2) is used for each end type of one end closed and both ends open.

If some suitable sound measurements around a groove or crack on a concrete wall can be executed, phenomenon can be recognized to be the resonance and the fundamental frequency of resonance can be caught. Therefore, we can estimate the depth of groove or crack to be 1/4 or half of the wavelength as according to the equation (1) or (2). By basis of the theory, series of more higher-order resonance phenomena can be caught at the same time and we can decide whether equation (1) or (2) should be applied. If the resonance frequency series are in odd number mode, equation (1) can be applied, and it can be judged as non-penetration with one end closed. The effective length L_e can be estimated to be the depth. By the same way, if they are in even number mode, equation (2) can be applied, and it can be judged as penetration with both ends open. L_e can be estimated to be the depth.

In order to catch sound resonance phenomena, many fundamental methods are thought out. To make sure the measurement techniques and the suitable practical estimating methods, multi layer model of different acoustic impedance accumulating under the condition of plane wave incidence as shown in Figure 2 was assumed. We calculated the acoustical characteristics around typical groove or crack based on this model and considered the effective estimation techniques.

The acoustic impedance Z_x of opening part, acoustic impedance Z_{surf}, acoustic admittance β_{surf}, complex sound pressure reflection ratio r_{surf}, sound pressure p_{surf}, particle velocity u_{surf} on the virtual observation area is obtained from the following equations. The sound pressure p_{rx} reflected to the area from the opening of a groove or crack is also obtained from the following equations,

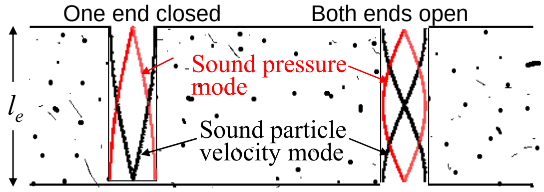

Figure 1. Acoustic resonance model of groove or crack on concrete block/wall

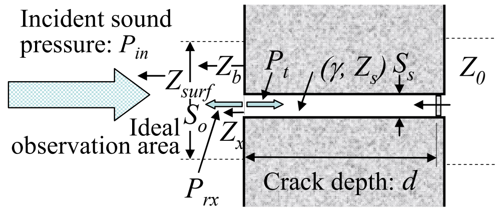

Figure 2. Calculation model imitating the groove or crack on concrete block/wall

$$Z_x = \left(\frac{Z_g}{S_g}\right)\frac{Z_{back}\cosh\gamma d + (Z_g/S_g)\sinh\gamma d}{Z_{back}\sinh\gamma d + (Z_g/S_g)\cosh\gamma d}, \tag{3}$$

$$Z_g = Z_0/S_g = \rho c/S_g \tag{4}$$

$$Z_{surf} = \frac{Z_b Z_x}{Z_b + Z_x}, \tag{5}$$

$$r_{surf} = \frac{Z_{surf} - Z_{in}}{Z_{surf} + Z_{in}}, \tag{6}$$

$$p_{surf} = (1 + r_{surf})p_{in}, \tag{7}$$

$$\frac{p_t}{Z_x} = \frac{(1 - r_{surf})p_{in}}{Z_{in}}, \tag{8}$$

$$\frac{P_{rx}}{Z_{in}} = \frac{P_t}{Z_x}, \tag{9}$$

$$P_{rx} = (1 - r_{surf})p_{in}, \tag{10}$$

$$\beta_{surf} = 1/Z_{surf}, \tag{11}$$

$$u_{surf} = \beta_{surf}\, p_{surf}, \tag{12}$$

where, Z_o and ρ are the acoustic impedance in air and the density of air. S_g, γ and d are the opening area, the sound propagation constant and the depth of groove or crack. Z_{back} is the impedance at the back end of groove or crack. If the one end closed, Z_{back} =∞ is assumed, and if both ends open, Z_{back} is assumed as to be the impedance Z_0 as same as in the air or as to be ideal Z_o/S_o. As for virtual observation surface area, Z_b is the impedance excluding the opening of groove or crack, S_o is the virtual observation surface area including the opening of groove or crack and Z_{in}= Z_o/S_o is characteristic impedance in the observation area. P_t is the penetration sound pressure into the groove via the opening from the sound source side. The sound pressure and the particle velocity in each part are calculated as the ratio to the incidence sound pressure P_{in} to the observation area. P_{in} cannot be measured independently but p_{surf} including p_{in} can be measured very easily.

Some calculations for the one end closed type tube with the length of 85.8mm were done by using these equations, and calculated results of acoustic sound pressure and acoustic particle velocity around the opening of the tube are shown in Figure 3. By this size, fundamental resonance frequency is calculated to be 1000Hz by equation (1). Also acoustic admittance for the both end open type tube is shown in the same figure. It is clearly understood that the frequency of peak and dip by sound resonance phenomenon are different for each condition.

Observation method of resonance phenomenon

To catch resonance phenomena, various methods are expected. Three typical methods are introduced from our experiences of past researches. [3][4] We search their possibilities for practical use.

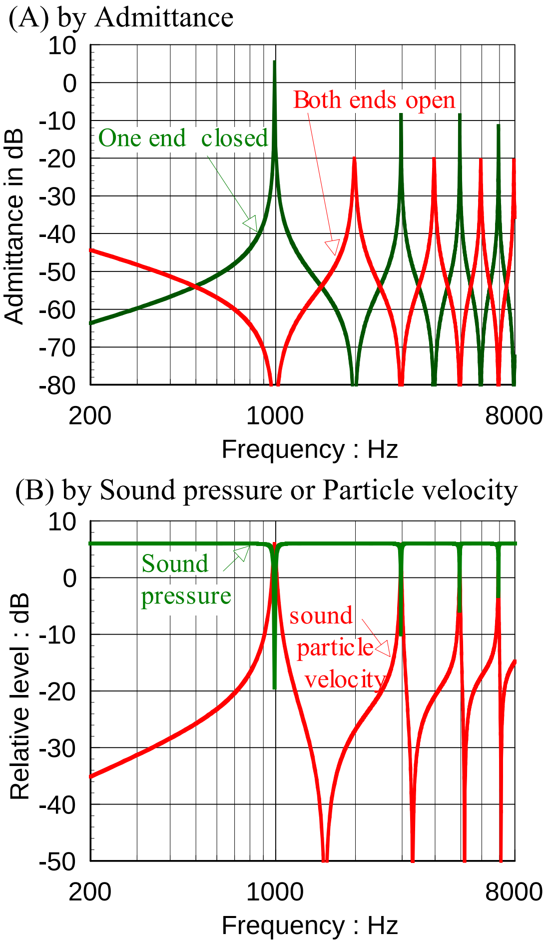

Figure 3. Calculated resonance responses in admittance, sound pressure and acoustic particle velocity

The first method of them is observing the response of resonance phenomena caused by sound wave excitation to the detection object. We call such response “resonance response” after this. As in the example shown in Figure 3, the sound pressure response keeps constant high value for wide frequency range, and has very narrow dips only at the resonance frequencies. On the other hand, the particle velocity keeps low value for wide frequency range, and has high peaks at every resonance frequencies. It is clearly understood that the acoustic admittance, the ratio of particle velocity to sound pressure, indicates very sharp high peak values by the resonance phenomena as well as the response of the particle velocity because acoustic resistance is not taken account in the propagation constant γ.

The method of observing particle velocity response or admittance can catch the peak at resonance frequency more plainly than the method of observing the sound pressure response catchs the very narrow dip at the resonance frequency. So, the former is judged to be a dominant method.

Next, the observation by an extremely minute microphone inserted in the crack may be effective if limited to the sound pressure observation. However, the method is ideal and to put into practice is difficult now. For these methods, idea of high-sensitive catching of the response from the crack opening and rejecting the very strong incident test sound wave are needed.

As the last, method similar to wind instrument as different from the methods using sound wave exciting is expected. It is a method of catching the generated sound at fundamental resonance frequency and its overtones when air is blown to the opening of groove or crack.

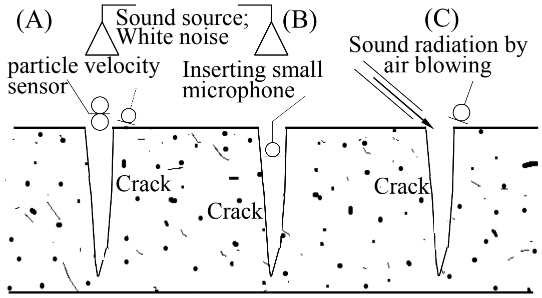

Figure 4. Three examples of the detection method of crack depth based on sound resonance phenomenon

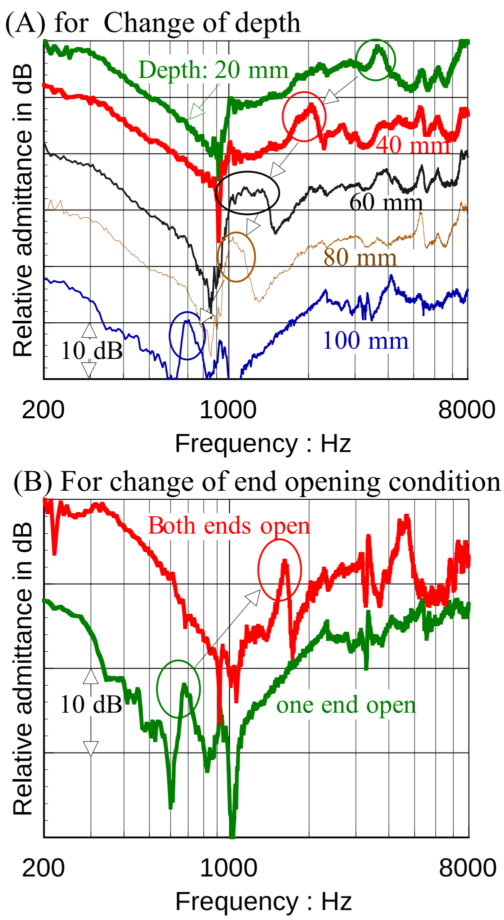

Figure 5. Changes of resonance responses by different depth and by different opening condition

Three method models observing the resonance phenomenon are shown in Figure 4 (A), (B) and (C).

EXPERIMENTAL OBSERVATION

Verification experiments by basic test sample

At first, simple test sample formed by the surface mating of a couple of aluminium-board was prepared for basic observations of the resonance phenomena. Depth and width of the air gap of this test sample were able to be changed for each condition by using plastic sheet spacer. The sound wave signal of white noise was radiated from a loud speaker at height of about one meter or lower to the opening of the air gap on the sample. Then, responses of both sound pressure and particle velocity were recorded on a PCM recorder by arranging a pressure microphone and an old type Microflown’s hot-wire particle velocity sensor on the opening of groove in parallel.

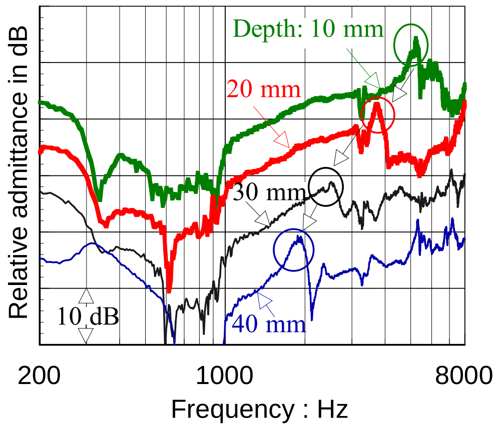

Figure 6. Observed resonance responses on the samples made by concrete block with different groove depth

Recorded wave type files were sent to a personal computer and analysed by the FFT software.

Analyses of both spectra of sound pressure and acoustic particle velocity, the transmission function of particle velocity to sound pressure, the power coherency between both values, etc. were simply executed at the same time. This transfer function means the relative acoustic admittance without calibration test. The analysed result of each depth of the air gap from 20 to 100mm is shown in Figure 5 respectively.

In the upper figure, the peaks at different fundamental frequencies of 3.6, 2.0, 1.2, 1.0 kHz and 700 Hz are recognized. Next, for both end conditions of one end closed and both ends open on the air gap with the same depth of 100mm, the resonance responses are compared in the lower of the same Figure 5. The peak of fundamental resonances mode appears at each frequency of about 700Hz and 1.5 kHz. The sound resonance in the air gap imitating crack were recognized by the peaks of acoustic admittance, and effective length L_e is calculated to be 122mm for 700Hz giving to the equation (1), and also calculated to be 113mm for 1.5 kHz to the equation (2). It was understood that sound resonance phenomenon would appears in crack on a wall and roughly would correspond to the theory of air column resonance.

Experiment on more complex conditions

The verification experiments by some kinds of groove test sample imitating actual crack structure were executed. Groove test samples were formed on the thick concrete block made by raw mortar and surfaces in the groove were rougher than that of aluminium-board and might have a little acoustic resistance. Examples of observing the acoustic admittance on the four test samples with groove depth of 10, 20, 30 and 40 mms are shown in Figure 6. It can be confirmed that peak by sound resonance phenomenon appears at different frequency depended to the each depth of groove.

As for narrowness of groove, the observation experiments were done using the test samples of aluminium-board again in the same condition of air gap depth of 40mm and by changing width from 0.2 up to 1mm and 0mm for the reference. The results are shown in Figure 7. It is confirmed that the peak of the resonance response becomes duller with decreasing the width of groove. Invention of increasing sensitivity to catch resonance response for estimating on narrower crack is necessary. For the test sample that increased the acoustic resistance in groove, a cleavage was generated by force-pressing a concrete flagstone with a thickness of 40mm was prepared. To obtain the test sample of one end closed type, both divided planes with roughness were matched again

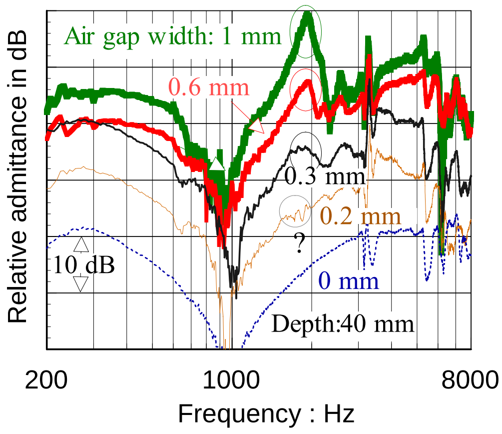

Figure 7. Comparisons of observed resonance responses on samples with air gaps of 0.2-1.0 mm width

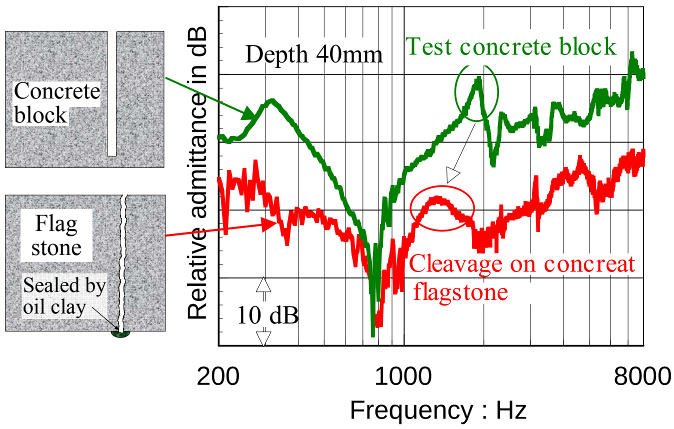

Figure 8. Comparison of observed resonance responses on a concrete block sample and cleavage on a concrete flagstone with the same depth of 40mm

and the back sealed with oil clay. Groove of this test sample was composed of a non-straight line as divided plane as it was, and it was more similar to the crack on actual concrete wall. The observed result is shown in Figure 8 and the reference result on a concrete block is shown together in the same figure. The peak observed at about 1.5 kHz is less sharp than the test sample of the aluminium-board. This frequency dose not correspond well to equation (1). It can be thought that the reason is in the winding of groove as maze formed by divided surfaces of the cleaved flagstone.

Finally, the observation method of the self-generated sound by blowing air to the opening as illustrated in Figure 4(C) was tried. Two examination objects are the straight line type test samples with 30mm depth on concrete block and non straight line type test samples of the cleaved flagstone board as above-mentioned.

Compressed air was blown to the opening of each test sample, and the spectral analysis on each generated sound for timelength of about 20 or 40 seconds wave was done. Each analysed results in the low frequency resolution of evry 25Hz is shown in Figure 9. In this figure, aparant smooth spectrum peak at each frequency of 1.5 kHz and 2 kHz is observed, and each frequency where peak appears is near the frequency of the peak observed in the analysed results of acoustic admittance. This fact suggests the possibility of more different observation ways for resonance phenomena. Measurement instruments of the method of blowing air are very simple and it is easy to understand its principle. Then, we can hear the condition of crack by the tone. However, it found out that application to the very narrow crack is difficult.

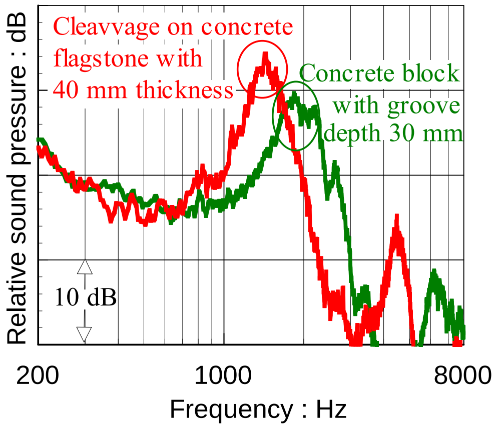

Figure 9. Comparison of generated sound by air blowing to a concrete block sample and cleavage on a concrete flagstone

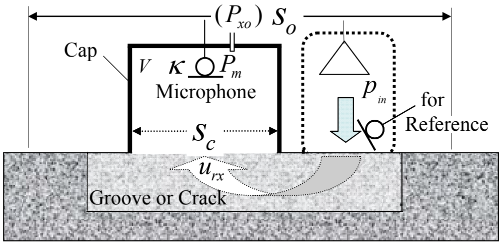

Figure 10. Receiving method for only the sound wave through resonance crack by using a small microphone covered by sealing cap to reject the direct incident sound wave

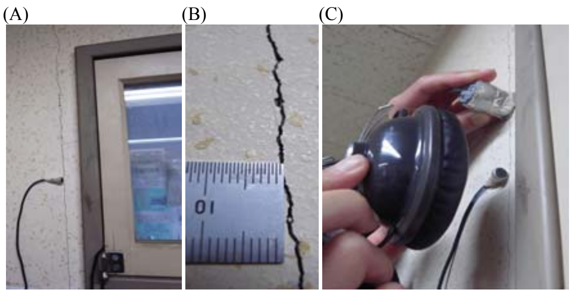

Photo 1. A test target crack of a window side on a wall (A), its zoom up view(B) and Observation set-up with head phone for sound excitation on reference microphone and a little distant receiving microphone sealed by metal cap(C)

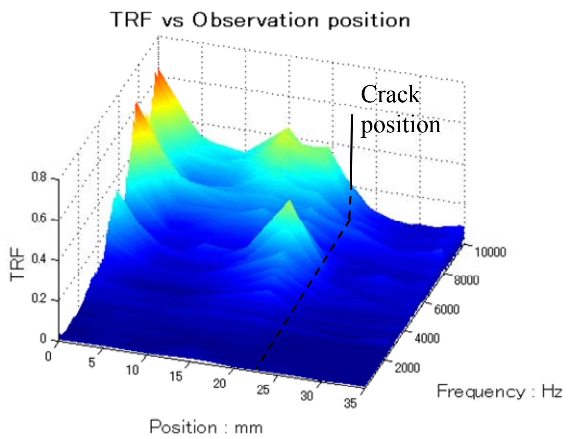

Figure 11. Vibration distribution along the direction crossing the crack on a wall, and the sudden decreasing of amplitude indicates existing of a crack; but its depth cannot be known

EXPERIMENTS ON ACTUAL BUILDING WALL

To make sure the outlooks of these methods for practical use, the sound measurements and the analyses were executed on the cracks appeared on actual building walls. Then, the estimations of crack depth were tried. In the analysis of the sound measurement around crack opening, it is understood that the particle velocity and the acoustic admittance value is effective to recognize resonance phenomena as above-mentioned.

Since popularities of the particle velocity sensor in many research institutes are still low, possibility and effectiveness of handy sound measurement method only by the microphone at this stage were searched for this measurement aim.

As the most important fact, it is pointed out that acoustic particle velocity has maximum value at the opening of groove or crack as at the loop of the air column resonance. If only radiated particle velocity u_{rx} from the opening can be led to a closed small space formed by a sealing cap as shown in Figure 10, the sound pressure p_m reproduced in the space as according to the following equation, [5]

$$\kappa \frac{\Delta V}{V} = p_m, \tag{13}$$

$$\Delta V = S_c \Delta x_{rx} = S_c \int u_{rx} dt = \frac{S_c u_{rx}}{j\omega}, \tag{14}$$

$$P_m = \kappa \frac{\Delta V}{V} = (\rho c^2) \frac{S_c u_{rx}}{j\omega V} = \frac{c S_c (\rho c u_{rx})}{j\omega V}, \tag{15}$$

$$p_{xo} = \left(\frac{S_c}{S_o} \right) \rho c u_{rx} = \frac{j\omega V}{c S_o} p_m, \tag{16}$$

where, V is the volume of closed small space, κ is the bulk modulus of air, ΔV is the virtual volume change cause by particle velocity, Δx_{rx} is the virtual displacement by u_{rx}, ω is angular frequency and j is the imaginary number unit. As in the equation (15), u_{rx} corresponding to the resonance strength directly reflects on the sound pressure. Reproduced sound pressure by particle velocity and measured by the microphone set up in the closed small space p_m indicates the maximum value at the resonance frequencies.

Then, unnatural frequency characteristics with the emphasis at low frequency and the weakness at high frequency is added to the measured sound pressure p_m as the description ω in the denominator in equation (15). By the correction calculation using equation (16), sound pressure equivalents to the sound pressure when only u_{rx} virtually radiates in open air p_{xo} can be obtained and it has the natural frequency characteristics.

Observation experiments

In this study, the observation method described just above is realized by a microphone with the sealing heavy cap cover and by close contacting to the opening of groove or crack. Strong incidence sound wave signal for the test is excluded.

Phot 1 shows the over view and the zoom up view of target actual crack. In this picture, the one unit of a headphone-set for sound excitation and both electret small microphones for the referring sound excitation and for the observing resonance response by the covering of a metal cap are shown.

Before the observation of sound resonance phenomena caused in the actual crack on a concrete partition wall, we tried the rough research on crack depth by the observation of vibration distribution using laser Doppler vibrometer. By 3-D display, the observed frequency characteristics of vibration on the array points as crossing the crack at right angles.

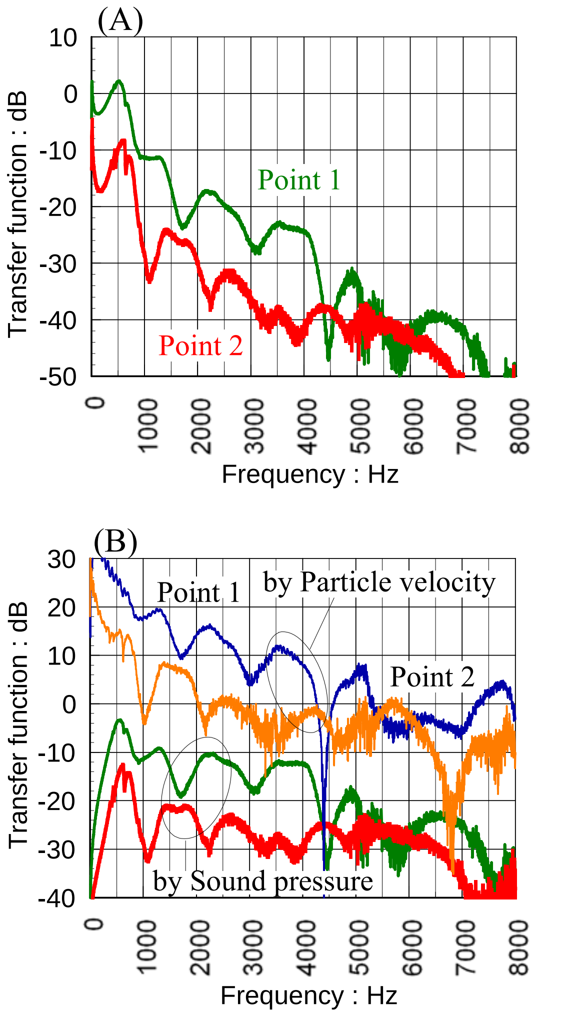

Figure 12. (A) Analysed examples of measured at two points on a crack opening by the method shown in Figure 10, (B) their corrected results by the equation (16) and observed results by a particle velocity sensor

Observed example at when the vibration of white noise signal was excited by a piezo-electricity device at a near point of the crack is shown in figure 11. The sudden decreasing at just crossing crack is clearly shown. The object actual crack seemed not to be shallow.

The resonance phenomena reflect on the sound wave by passing through the groove or the crack. Examples of observed results at two points are shown in Figure 12 for the crack on a partition concrete wall of a building. Many gradual peaks recognized in the wide frequency range though the level in low frequency range has risen relatively when not corrected as they were measured as shown in (A). The corrected results by Equation (16) are shown in (B) and many peaks can be naturally observed even in higher frequency range. In the same figure, observed resonance responses by the recent Microflown's hot-wire type particle velocity sensor are shown for the comparisons. Both frequency characteristics results of particle velocity and of sound pressure with correction by the equation (16) almost matched each together.

As for point 1, the peak is observed at frequency of 600Hz as the lowest resonance mode, and peaks are observed at the frequency of 1.2 kHz and about 2.2 kHz as the higher-order modes. From these results except the peak at frequency of 600 Hz, we can estimate that the test target is penetration type crack with depth of about 140mm. In fact, the crack fortunately could be recognized by eye at the same position

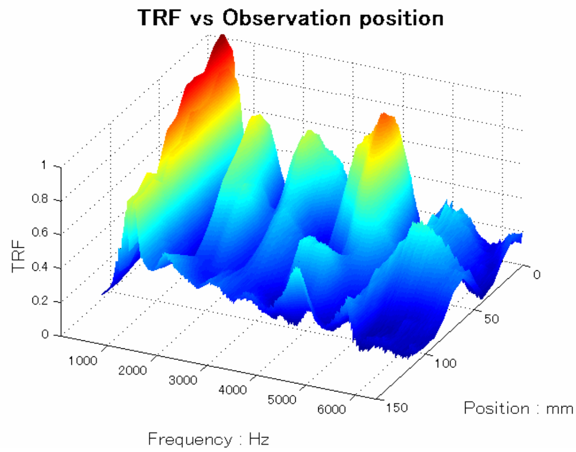

Figure 13. 3-D Display of resonance response at each observation point along line of crack on the wall shown in Photo 1

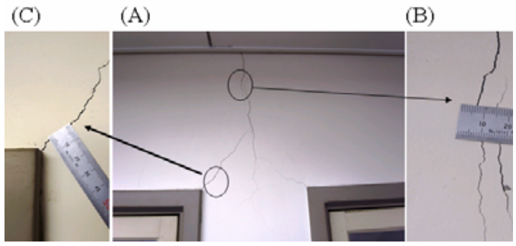

Photo 2. View of one of other actual object cracks on a concrete wall in a building different from former example shown in photo 1(A), Zoom up view of the crack 1(B) and Zoom up view of the crack2

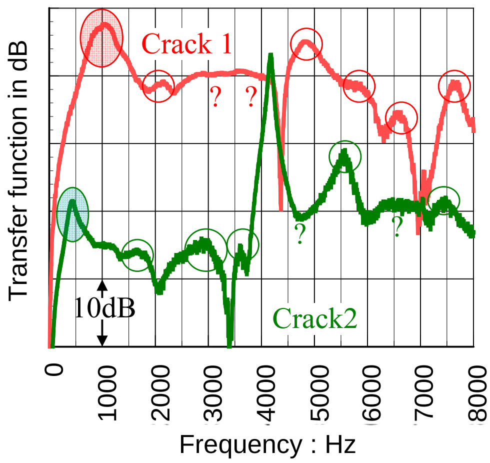

Figure 14. Analysed examples measured on the two cracks on a wall in another building; both cracks depths seem to be about 170mm but both seem different one end closed and both ends open respectively

in the rear side of the wall with thickness of about 125mm. It is guessed that the peak at the frequency of 600Hz shows the existence of non-penetration type as the partial blockade in the crack. As for point 2, second and third peak frequency are higher than at point 1. The crack strongly seems to be un-penetration type and its depth is estimated to be 180mm.

In this example, it is understood that the odd number sequence of frequency of response peak and the even number sequence has been mixed each other and that the un-penetrative characteristics can be observed in actual penetration type crack. In general, rear side of the wall cannot be observed by eyes. Then, responses at consecutive array positions for the more detailed estimation are necessary as shown by 3-D display in Figure 13. A regular peak row can be observed, and resonance phenomena roughly correspond to the depth of 150mm that exceeds the thickness of the wall a little.

We can confirm that estimated depth is deeper than the thickness of the wall because actual crack has non-straight diversion sound path like a maze. We point out that narrow sound path as in porous material has low sound propagation speed at low frequency [6] [7] and that such characteristics of sound speed and the longer sound path as in the maze makes resonance peak frequency lower in the low frequency area.

Next, we selected other actual examples of two cracks on the same wall as shown in Phot 2. Rear side of the wall was hidden by the ceiling board, so both crack types could not be recognized from the observation by eyes but thickness of the wall at a visible near point could be estimated to be about 160mm. From obtained results of response shown in Figure 14, existences of two states of crack as one end closed by lowest peak at about 500Hz and both ends open by the peak at about 1 kHz can be estimated. It is similar to the above-mentioned results. However, peaks by higher mode resonance are not clear than former examples. The reason of unclearness of the higher mode resonance may be due to the thicker wall that causes the certain acoustic resistance. In addition, it is confirmed that deep dip of at 4300Hz and very high peak at 4100Hz are not resonance responses of crack but the reflections of characteristics in sound source and radiation.

SOME EXAMINATIONS FOR PRACTICAL USE

It is necessary to accumulate the observation experiences for the error-less judgments on the crack depth and on the corrections for observed result of resonance response. Some examples of our considerations are introduced as the followings.

Detection of deeper crack

"Width of crack is narrow" and "crack is deep" are the biggest factors of the difficulty in the depth detection. The test sample with face matching of a pair of concrete panel with size of 1(length)×0.3(width) ×0.3(thick)m^3 was prepared, and the detection experiments for deeper groove structures were done. Width and depth of the air gap between two panels could be adjusted by inserting the vinyl chloride spacer with the thickness of 1, 2, and 3mm. The observation result is shown in Figure 15.

Figure 15(A) is example to observe by the particle velocity sensor on the opening. Figure 15(B) is an example of the result using the microphone with a sealing up cover. When width of the air gap is 1mm, it is impossible to observe the peak in low frequency resonance mode.

However, higher modes can be observed as the row of resonance response peak. The mean frequency interval is obtained by reading of consecutive peaks. For example in Figure 15(A), eight peaks exist between 600Hz and 2600Hz. By averaging, the mean frequency interval becomes 1200Hz and leads to the depth to be 850mm by the equation (1). It is understood that this result corresponds to 880mm of the setting extremely well. It seems that this estimation method is expected for deeper depth and narrow crack occurred on the concrete structure with thick wall and large-scale size.

We point out that dangerous crack is deeper and wider, and the wider width of crack decreases difficulty in the diagnosis. Then, dangerous crack makes the sign with clear repeating appearance of a pair of peak and dip with narrow frequency interval starting from low frequency to high as example of the resonance response on 3mm width in the Figure (15) both (A) and (B).

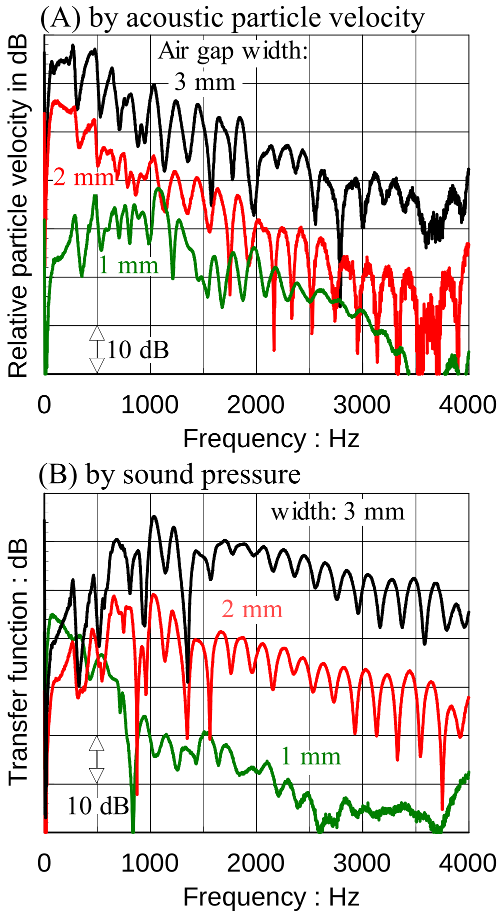

Figure 15. Comparisons of resonance response by both way acoustic admittance and only by microphone on more deep air gap with the same depth of 880 mm and different widths of 1, 2 and 3 mms on the test samples made of concrete panel

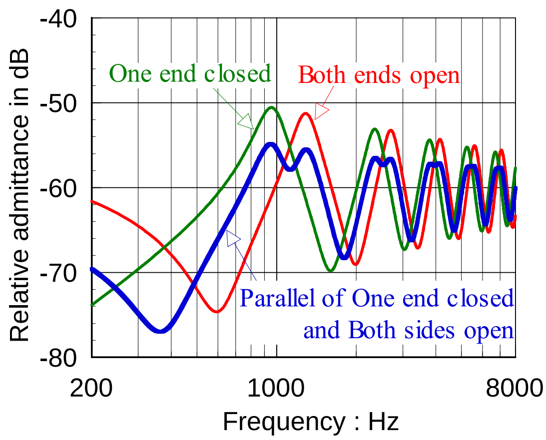

Figure 16. Simulated result of resonance response for the paralleled cracks of one end closed and both ends open

Coexistence of different stats of end opening type

There are many type cracks as with the coexistence of both types of one end closed and of both ends open, with different depth in bottom and with partial blocked point, etc. To solve one of such subjects, the response in a parallel states of crack types of one end closed and both ends open was considered. Most simply, the response based on the paralleled acoustic impedances for both type end conditions was calculated by equations from (3) to (12). Figure 16 shows the example of calculated results.

The reflection of coexistence of two crack types in the resonance response can be read. Such simulating calculation will help us at the reading and consideration on the observed results as on the actual crack already introduced in Figure 12 and Figure 13.

In this case and in actual observation, it has to be made sure that response is not obtained as the average depth when states with different conditions are ranged at the bottom of crack but that the response appeared as gently extended peaks in parallel according to the states. It is important to read the over all response tendency by continuously arranged observation points as example shown in Figure 13.

Effect of section shape of crack on response

In addition, the effect of shape change of the crack on the resonance response were calculated by repeating use of the equation (3) by the dividing to many thin section layer and changing the value of S_t from narrow to wide for both trapezoid and triangle section type in each end opening conditions of one end closed and both ends open. Calculated examples are shown in Figure 17. As for one end closed, effects of the difference of section shape of crack appeared in the resonance response. When the shape changes from rectangle to trapezoid and triangle, resonance mode frequencies become higher and they mean that effective depths become shallower. On the other hand, as for both ends open, resonance mode frequencies become lower only in the case of triangle shape and it mean that crack close to one end closed type.

CONCLUSIONS

We could find out the sound resonance phenomenon in the groove structure similar to the air column resonance. From the consideration of principle on the observation method of sound resonance, we could propose three detection methods of the crack depth based on the sound resonance theory.

By observing particle velocity and admittance and by analysing the generated sound by air blow to the opening of groove, we executed acoustical experiments to recognize the effectiveness of proposed detection methods by using test samples of air gap or groove type structure made of aluminium-board material and of concrete mortal. Then, we could have some main conclusions as the followings.

1) It can be understand that the resonance appears in the groove structure including crack as according to the air column resonance theory.

2) It is possible to estimate the depth of crack and its opening state based on the reading frequencies of resonance peaks and the reading the series of peaks caused by higher-order resonances.

3) It can be understood that particle velocity observation method is effective and sound receiving by microphone with the sealing cover is effective. .

4) These methods were able to apply to the actual crack of a wall in a typical building, and complicated state could be recognized.

5) Tendency is appeared in the observation of first mode peak at low frequency is not easily for deeper and narrower crack. However, the row of peak by higher-order resonance can be caught and the crack depth can be estimated.

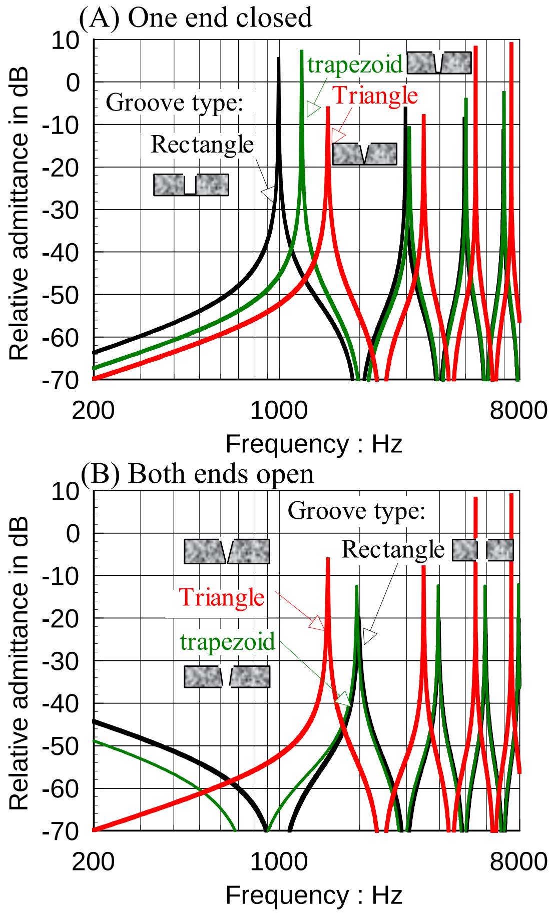

Figure 17. Simulated results of resonance response for the three section types of groove imitating crack

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