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**PAPER**

# Location of a defect in a concrete block by a non-destructive technique

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**Abstract:** This paper describes a method to estimate the position of a crack in a concrete block using several vibration pick-ups. An array of vibration pick-ups is attached on the concrete block, and a vibration pulse is forced by using a small hammer. If there is a crack, a reflection wave is generated from the position of the crack. Therefore, conventional methods to estimate the position of vibration source seems to be useful for this purpose. However, since the concrete block is elastic, there are three wave propagation modes; the surface wave mode, the primary wave mode and the secondary wave mode. Since the necessary primary wave mode is not significant in magnitude, we cannot estimate the position by the conventional methods. To increase the S/N, we had already proposed a method to eliminate the first-coming surface wave. However, the method was insufficient to achieve a higher S/N. Therefore, this paper proposes a new method to achieve a better location of a crack. Some experiments were carried out, and good results were obtained.

**Keywords:** Non-destructive measurement, Vibration, Multiple sensors, Beamforming

**PACS number:** 43.40.Le

## 1. INTRODUCTION

Non-destructive methods to find a crack in a concrete block are divided into two categories: (1) a method using X ray and (2) a method using a vibration signal. Since the first one costs a lot, the second one is widely investigated. Since the concrete block investigated in our project is vary large, we uses a low frequency vibration signal instead of a ultrasonic. Conventional method using the low frequency vibration signal drives the concrete block with a vibration force, and estimates the resonant frequency of the concrete block, by which the position of the crack is estimated [1,2]. However, this method only works well in the cases: (1) the crack is just like a sheet and the sheet is parallel to the surface of the block (standing wave is generated in this case), or (2) the crack is big so that it causes the shift of the resonant frequency. This paper describes another method to estimate the position of a sheet-like crack in a concrete block using several vibration pick-ups. In our method the position of the first reflection wave from the crack due to the vibration force is used to find the position of the crack instead of the resonant frequency. The positions of cracks can be estimated by our method when the concrete block has more than one crack, while it is very difficult to estimate the location by the conventional method. Furthermore, this method may work well even in the case that the sheet-like crack is slant to the surface of the concrete block, but this paper deals with only a block having one or two cracks which are parallel to the surface. The problem about the slant crack remains as the future work.

In our method an array of vibration pick-ups is attached on the concrete block, and a vibration pulse is forced by using a small hammer. The hammer produces low frequency components, which does not decrease in power compared to a higher frequency component, and the reflection from a crack, which is at a deep location in the block, can be detected. Since the concrete block is elastic, there are three wave propagation modes; the surface wave mode, the primary wave mode and the secondary wave mode, and the necessary primary wave mode is not significant in magnitude. This problem can be neglected in the conventional method which estimates the resonant frequency, but is serious in our method. To increase the S/N, we had already proposed a method to eliminate the first-coming surface wave [3]. However, the method was insufficient to achieve a higher S/N because of the multiple reflections from side walls. This paper proposes a new method to achieve a better estimation by eliminating the reflections from side walls. It is found from some experiments that the position of a crack can be detected clearly by our method.

## 2. EXTRACTION OF ONLY THE PRIMARY WAVE

It is assumed that there is an elastic block with a crack as shown in Fig. 1.

Several vibration pick-ups are attached on the air side of the block, and almost the center of the array of the pick-ups is hit with a small hammer. Considering the mirror effect, a reflection wave can be assumed to be the direct wave from the corresponding image source [3]. The position of the crack is estimated by the position of a peak in the output of a sensor output from the crack using a sphere field beamforming technique [4].

An example of the waveform of a sensor output is shown in Fig. 2.

The vibration wave $x_m(t)$ at the $m$-th pick-up due to the direct sound, which is caused by a hitting with a small hammer, is represented as follows:

$$x_m(t) = a_{h,m}\delta\left(t - \frac{r_{h,m}}{c_t}\right) + \sum_p \left\{ b_{p,m}\delta\left(t - \frac{r_{p,m}}{c_p}\right) + c_{p,m}\delta\left(t - \frac{r_{p,m}}{c_s}\right) \right\}, \quad (1)$$

where $a_{h,m}$ is the attenuation coefficient for the surface wave from the hitting point to the $m$-th pick-up, and $b_{p,m}$ and $c_{p,m}$ are the attenuation coefficients for the primary and the secondary waves from the $p$-th real or image source to the $m$-th pick-up, respectively. $\delta$ is the delta function, $r_{*,*}$ the propagation distance, and $c_t$, $c_p$ and $c_s$ are the velocities of the surface, the primary and the secondary waves, respectively.

We had proposed a method to eliminate the surface wave to achieve a higher S/N [3]. However, the method is insufficient because of the following reasons:

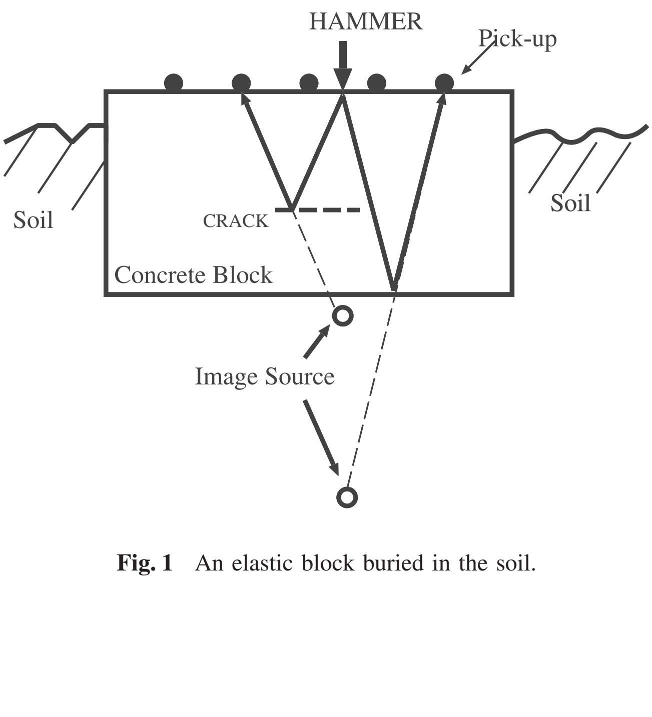


**Fig. 1** An elastic block buried in the soil.

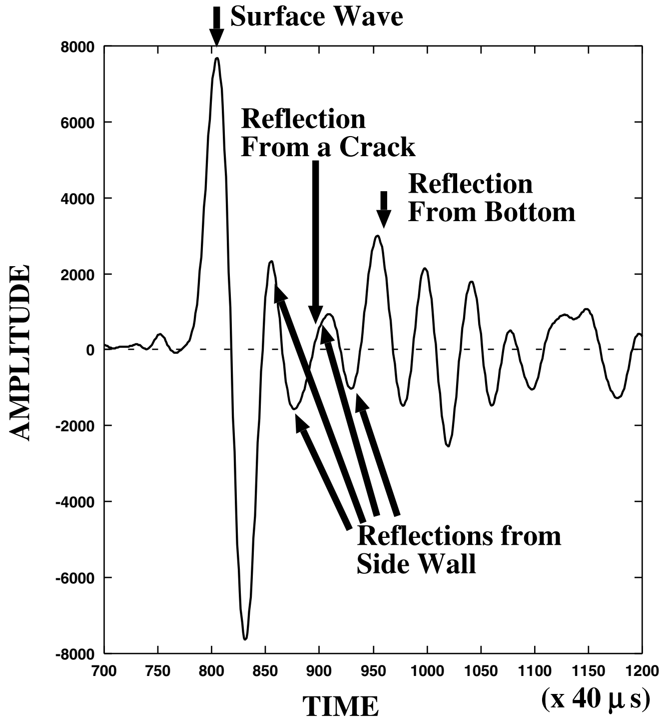


**Fig. 2** An example of the waveform $y_m(t)$ of a sensor output.

(1) since the sensor outputs were passed through charge amplifiers and the hammer pulse cannot be represented by the delta function.
(2) the concrete block used in the experiment was a rectangular parallelepiped, and many refections from the walls were generated.

If the distance between the hitting point and the sensor is sufficiently longer than the width of the concrete block, periodical reflections are observed as shown in Fig. 2.

That is, the output $y_m(t)$ of the $m$-th charge amplifier is expressed as follows:

$$y_m(t) \approx x_m(t) * h_a(t) * h_{c_m}(t), T_{0m} \leq t \leq T_{bm} \quad (2)$$

where $T_{0m}$ is the time when the fastest wave due to the hitting with a hammer reaches the $m$-th sensor, $T_{bm}$ the time when the reflection from the bottom boundary reaches the $m$-th sensor, $*$ denotes the convolution integral, $h_a(t)$ the impulse response of the charge amplifier and $h_{c_m}(t)$ the impulse responses for $m$-th sensor due to the reflections from side wall. Since the proposed method could eliminate only the first positive peak, the successive part of the surface wave and its reflections from the side wall, whose power is greater than that of the primary or secondary wave, remain unchanged. Therefore, the necessary reflection pulse cannot be observed clearly even by the previously proposed method [3]. Furthermore, since many reflections overlaps each other, it is difficult to estimate the attenuation coefficients, and the necessary primary wave could not be extracted even by the method.

Therefore, this paper describes a new method to achieve a higher S/N as follows:

(1) Let $y_1(t)$ the output of the pick-up which is the nearest to the position of the hitting.

(2) Subtract $d_m y_m(t-\tau_m)$, $m \neq 1$ from $y_1(t)$, where $d_m$ and $\tau_m$ are the constants and are determined so that the following error $E$ is minimum.

$$E = |d_m y_m(t-\tau_m) - y_1(t)|^2 \quad (3)$$

This processing works well since the distance between the hitting point and the sensor is sufficiently longer than the width of the concrete block, and the impulse response $h_{c_m}(t)$ due to the reflections from the side wall was almost the same for each sensor after compensating the time delay $\tau_m$. The remaining wave is the reflection from the crack and its reflections from the side wall.

Since the power of the surface wave is dominant, $d_m$ and $\tau_m$ may be chosen so that the effect of the surface wave becomes minimum, and the resultant wave $z_m(t)$ is expressed as follows:

$$\begin{aligned} z_m(t) &= y_1(t) - d_m y_m(t-\tau_m) \\ &= \sum_p \left\{ b_{p,1}\delta\left(t - \frac{r_{p,1}}{c_\mathrm{p}}\right) + c_{p,1}\delta\left(t - \frac{r_{p,1}}{c_\mathrm{s}}\right) \right. \\ &\quad - d_m b_{p,m}\delta\left(t - \tau_m - \frac{r_{p,m}}{c_\mathrm{p}}\right) \\ &\quad \left. - d_m c_{p,m}\delta\left(t - \tau_m - \frac{r_{p,m}}{c_\mathrm{s}}\right) \right\} * h_\mathrm{a}(t) \end{aligned} \quad (4)$$

Figure 3 shows an example of $y_m(t)$ and $z_m(t)$. It is easily found that not only the first positive peaks but also the successive negative and positive peaks due to the surface wave and its reflections from the side wall are decreased in $z_m(t)$. That is, the effect of the surface wave and its reflections from the side wall decreases. Then, the peaks due to the crack and other boundaries appear clearly in $z_m(t)$ as shown in Fig. 3.

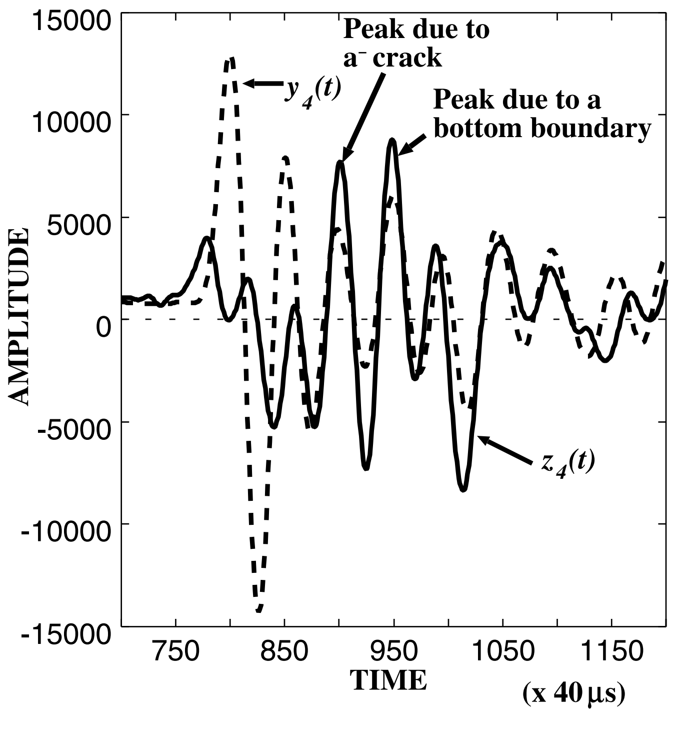


**Fig. 3** An example of $z_m(t)$ and $y_m(t)$.

## 3. NEAR FIELD BEAMFORMING

Since the positions of hitting point and sensors are known and the velocity $c_\mathrm{t}$, $c_\mathrm{p}$ and $c_\mathrm{s}$ can be estimated by the positions of the peaks in $y_m(t)$, the position of the crack is estimated by the near field beamforming [3].

In the method, an imaginary source is first assumed. Then, under the free field assumption, the distances between the imaginary source and all of the pick-ups are calculated, and all of the signals $z_m(t)$ are shifted in time domain to compensate the propagation delay. Then, the compensated signals are averaged. If the number of pick-ups is sufficiently large, the averaged compensated signal takes a large value in case that the position of the imaginary vibration source coincides with that of a real vibration source. Otherwise, it takes a small value.

The position of the imaginary vibration source is scanned in the space to be investigated. The estimated position of a real vibration source is the position where the value of the averaged signal yields a positive peak. (Since the impedance of the concrete is higher than that of soil or air, a negative peak is eliminated.)

Since the time of hitting and the velocity are known, the time, at which the reflection from the crack appears in the sensor output, can be estimated. To improve S/N, each sensor output was cut out with a time window, whose shape is the same as the output of the impulse hammer. Since the distance between the crack and each sensor was nearly the same in the experiment and the hitting point is near the sensor array, a circular-like pattern was observed, where the radius of the circular is double the distance between the hitting point and the crack. Hence, the pattern is not parallel to the surface of the block, but it is found from the position of the peak that there is a crack.

## 4. EXPERIMENT

Equi-spaced 6 pick-ups and two concrete blocks with the same size of 1.5 m × 3.6 m × 0.3 m were used for the experiment. One has a crack (crack #2 only), and the other has two cracks (crack #1 and #2) as shown in Fig. 4. The crack is a polyethylene sheet with a size of 0.5 m × 0.3 m × 200 $\mu$m. The velocity of vibration was 3,600 m/s for the primary wave, which was estimated from the period of the standing wave between the surface and the bottom boundary of the concrete block.

Figures 5–7 show the results of the near field beamforming, which are the absolute value of the averaged

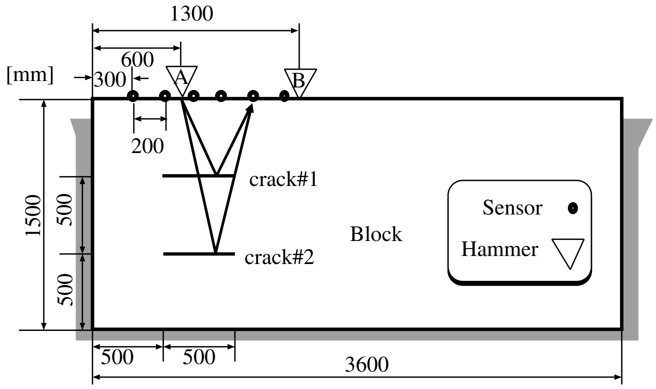


**Fig. 4** Pick-ups and a concrete block with a crack.

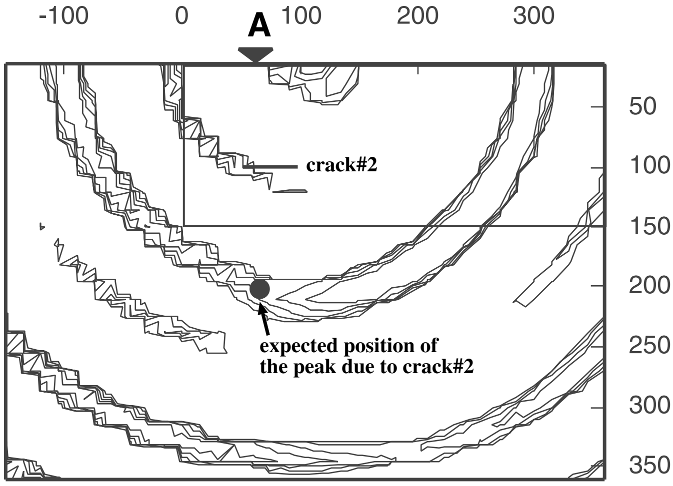


**Fig. 5** Result of the near field beamforming by the previously proposed method (hitting point: A, One crack #2).

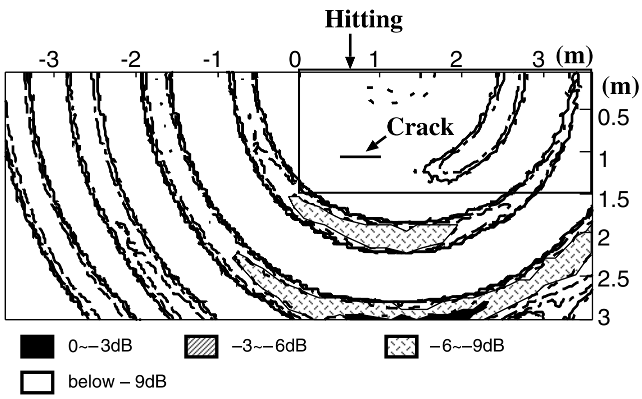


**Fig. 6** Result of the near field beamforming by the newly proposed method (hitting point: A, One crack #2).

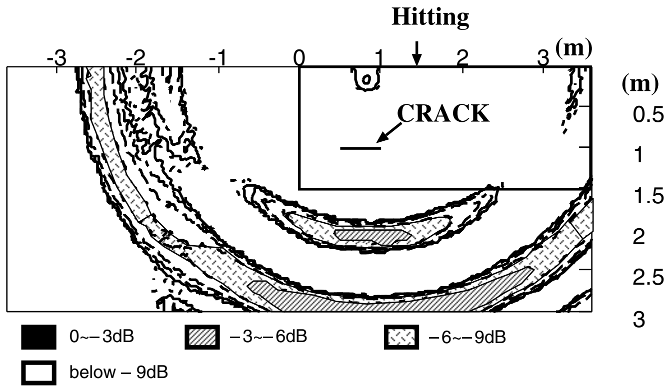


**Fig. 7** Result of the near field beamforming by the newly proposed method (hitting point: B, One crack #2).

power of a peak, which is illustrated by contour lines for the case of only one crack (crack #2).

Due to the mirror effect, a peak is expected at the position, where the distance between the hitting point and the crack is the same as that between the crack and the position of the peak. Also a larger peak is expected at the position, where the distance between the hitting point and the bottom boundary is the same as that between the bottom boundary and the position of the peak.

Figure 5 shows the result which was obtained by the previously proposed method where only the first positive peak was eliminated. It is found that the positions of the largest 4 peaks are not near the expected position. It is also found that there are many peaks in the unexpected positions, whose power is about the same as that of the peak in the expected position.

Figure 6 shows the result by the newly proposed method for the case of hitting point A. Two peaks due to the crack and the bottom boundary are clearly observed at the depths of 2 m and 3 m, respectively. Due to the mirror effect, the estimated position of the crack is just above the peak, and its depth is half the distance between the surface of the concrete block and the position of the peak. Thus, the estimated depth of the crack is about 1 m, and that of the bottom boundary is about 1.5 m. The position of the maximum value of the peak for the crack was a little different from the expected one, but the depth was almost the same.

The power of the peaks in the unexpected positions are less by more than 10 dB, and we can easily find whether a crack exists or not.

Figure 7 shows the result by the newly proposed method for the case of hitting point B. Two large peaks due to the crack and the bottom boundary are clearly observed at the depths of 2 m and 3 m as well as in Fig. 6.

It is found from Figs. 6 and 7 that by shifting the hitting point and the sensor array, the circular-like pattern changes but the real position of the real peak does not move. Therefore, we can locate the real peak due to the crack.

Figure 8 shows the result by the newly proposed method for the case of hitting point A and two cracks

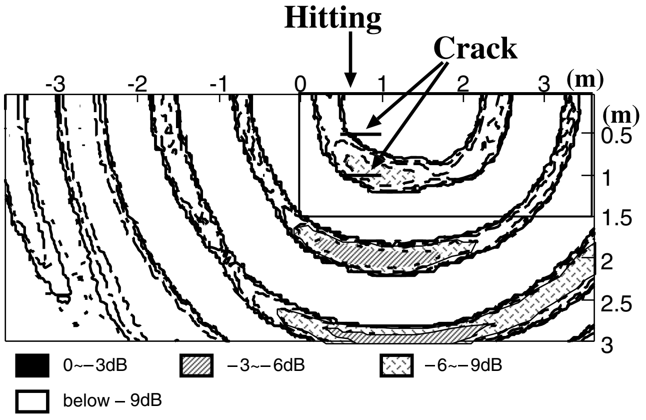


**Fig. 8** Result of the near field beamforming by the newly proposed method (hitting point: A, Two cracks #1 and #2).

(crack #1 and #2). Three peaks due to the two cracks and the bottom boundary are clearly observed at the depths of 1 m, 2 m and 3 m, which are double the depth of the crack #1 (0.5 m), #2 (1.0 m), and the bottom boundary (1.5 m), respectively. The peak at the depth of 2 m may due to the multiple reflections between the crack #1 at the depth of 0.5 m and the surface of the block, and there may be no crack at the depth of 1 m. In the case the value of the peak at the depth of 2 m should be less than that of the peak at the depth of 1m since the power of the wave decreases as the traveling path increases. Figure 8 shows, however, that the value of the peak at the depth of 2 m is higher by 3 dB than that at the depth of 1 m. This proves that the peak at the depth of 2 m is due to the real crack. But it is necessary to investigate the effect of the multiple reflections more precisely to find a small crack.

## 5. CONCLUSION

This paper described a method to estimate the position of a crack in a concrete block using several vibration pick-ups. Conventional method estimates the position of the crack by the resonant frequency of the concrete block, but this method does not work well in the cases: (1) the crack is not like a sheet, (2) the sheet is not parallel to the surface of the block, and (3) there are two or more cracks.

This paper described another method to estimate the position of a sheet-like crack in a concrete block using several vibration pick-ups. In our method the position of the first reflection wave from the crack due to the vibration force is used to find the position of the crack instead of the resonant frequency. It is found by an experiment that two cracks can be located by our method.

This method theoretically may works well even in the case that the sheet-like crack is slant to the surface of the concrete block. This remains as the future work.

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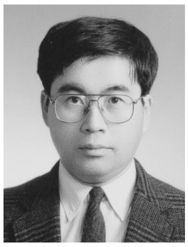

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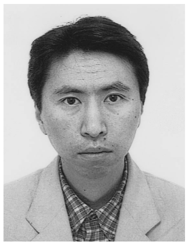

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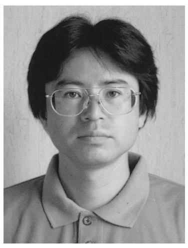

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