Measurement of the Diameters of Deformed Bars in Concrete Using an Electromagnetic Wave Radar (in the Presence of Cross Bars)

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Abstract: The authors previously proposed a method to measure the diameter of the deformed reinforcing bars in concrete structures nondestructively using an electromagnetic wave radar. The method estimates the periodicity of the knots of the inspected bar and utilizes the standard relationship between the knot’s pitch and the diameter of the bar to measure the diameter indirectly. The effectiveness of the method was verified using test specimens where the bars were placed parallel to each other. However, in practical case, where other reinforcing bars cross the inspected bar perpendicularly, the stronger reflections from the cross bars influence the reflection from the inspected bar. This paper thus proposes a general method which eliminates such unwanted influences from the cross bars and measures the diameter accurately even in practical environment.

Key Words: electromagnetic wave radar, diameter, cross bar, Kalman filter, maximum likelihood method.

1. Introduction

To check the integrity of concrete structures, nondestructive inspection is performed. But unfortunately, to measure the diameter of the reinforcing bars in concrete, there has been no effective nondestructive method in practice. Some attempts were previously made to assess the diameter using an electromagnetic wave (EMW) radar, for example, by Shaw et al. [1] and Chang et al. [2]. One of the methods [1] tried to analyze the B-mode image of the radar using a neural network, but it suffered from low measurement accuracy. The other [2] tried a digital image processing of the B-mode. But, this required an accurate priori information of the cover (or the depth) of the inspected bar. Moreover, these methods were only tested under controlled environments in laboratories where bars were arranged in parallel to each other.

From the view point, the authors previously developed a nondestructive method [3] using an EMW radar to measure the diameter based on the standard relationship between the diameter of a deformed reinforcing bar and its knot’s pitch. The knots are here defined as the protruding parts from the bar’s base, spaced at equal distance from each other along the length of the bar. In the method the knot’s pitch was first measured and then the true diameter of the inspected bar was measured indirectly based on the relationship.

In the method, an EMW radar was run in parallel to the inspected bar while keeping it in contact with the concrete surface, since it was the conventional way of scanning. During the scan, at each scanning point, the radar sent an EMW and was expected to receive the reflected signal from the point on the bar just below the radar. But the transmitter and the receiver of the radar being in contact with the concrete surface, a large angle of incidence of the transmitted EMW occurred on the bar. As a result, the frequency of the simultaneous reception of reflections both from the knot and the base of the bar increased and thus made it difficult to sort out and measure the propagation time of the EMW reflected from the point on the bar just below the scanning point.

Therefore, to overcome the difficulty, the authors further developed an improved method [4], which involved lifting off the radar during the scanning of the inspected bar and consequently minimized the frequency of simultaneous reception of reflections both from the knot and from the base. As a result, the accuracy of the measured propagation time of the EMW reflected from the point on the bar just below the radar was ensured. The obtained variation of the propagation times of the reflected EMWs from the bar along its length was then analyzed using a Kalman filter and a maximum likelihood method. By this method, a highly reliable measurement of the knot’s pitch (and consequently the diameter) was realized when applied to a test specimen having reinforcing bars parallel to each other.

But practically, in real structures, the bars are usually arranged in mesh pattern and the strength of reflection from a bar lying perpendicular to the scanning direction is greater than that from a bar lying parallel to the scanning direction [1]. Therefore, it becomes difficult to accurately measure the propagation times of the EMWs reflected from the inspected bar near the cross bars (even in the scanning with a lifted off radar).

Therefore, this paper proposes a new method to minimize the effect of the cross bars in the measurement process. The method introduces a criterion which links the usable smaller patches of variations of propagation times between cross bars along the length of the inspected bar and consequently ensures an accurate estimation of the knot’s pitch (and consequently the diameter).

2. Brief Overview of Our Previous Method

According to our previous method [3],[4], an EMW radar was used to scan along the length of the inspected bar over the concrete surface. At each scanning point, the received signal r(t) was modeled as the linear combination of the surface wave (the reflected wave from the surface) and the reflected EMW
from the deformed bar. The modeled signal \( r(t) \) incorporated the propagation times of the two respective waves, which were unknown.

The optimal propagation times of the EMWs reflected from the deformed bar were obtained by minimizing the pattern matching angle \([3],[4]\) between the actual and the modeled received signals. The matching angle \( \theta \) was defined as

\[
\theta = \cos^{-1}\left( \frac{r(t), \hat{r}(t)}{|r(t)||\hat{r}(t)|} \right)
\]

where \((\cdot,\cdot)\) and \(\|\|\) represented the inner product and the norm in Hilbert space respectively.

The periodic variation of the propagation times of the EMWs reflected from the bar (due to the presence of the knots at a regular spatial interval) was modeled as a linear combination of several sinusoidal functions with an additional bias as

\[
z(l) = z_0 + \sum_{i=1}^{l} z_i(l)
\]

where \( l \) represented the scanning distance and \( z_0 \) was a bias with \( z_i(l) \) defined as

\[
z_i(l) = a_i \sin(\omega_i l + \phi_i)
\]

where \( \omega_i = (2\pi/L)i \) (\(i = 1, 2, \cdots, n\)). Here, \( L \) corresponded to the knot’s pitch and \( \{\phi_i\} \) denoted the initial phase angles.

By defining the state vector as \( x(l) = (z_0, z_1, z_1, z_2, z_2, \cdots, z_0, z_0)^T \), the variation of the propagation time was modeled as an output of a dynamic system \( x(l) = A(l)x(l) + w(l) \) and the observation equation was modeled as \( y(l) = Hx(l) + v(l) \). Here \( A(l) \), \( w(l) \) and \( v(l) \) represent the transition matrix, transition noise vector and observation noise respectively. Also \( H = [1 \ 1 \ 0 \ 1 \ 0 \ 1 \cdots \ 0] \) was a \((1 \times (2\pi + 1))\) row vector.

The estimation of \( x(l) \) was performed using a Kalman filter \([3]\) by assigning different values to \( L \). The optimal value of the knot’s pitch \( L^* \) among the assigned values was determined by maximizing the likelihood function

\[
J = \prod_{k=1}^{K} p\left(y_k/L, Y^{k-1}\right)
\]

with respect to \( L \), where \( p\left(y_k/L, Y^{k-1}\right) \) is a conditional probability density function of \( y_k \) for a given observation sequence \( Y^{k-1} = \{y_1, y_2, \cdots, y_k\} \) and an assigned value of \( L \).

### 3. Proposed Analysis Method

A drawback of the previous method is that it cannot be applied directly to the actual case where the bars are arranged in a mesh pattern as shown in Fig. 1. The reason is that the transmitted signal by the radar is polarized in such a way that the reflection from a bar perpendicular to the scanning direction is stronger than that from a bar parallel to the scanning direction \([1]\). As a result, around the vicinity of a cross bar, the reflected EMW signal from the bar interferes with the EMW signal reflected from the inspected bar. In fact since in our received signal model, at each scanning point, we are only considering single reflection from the inspected bar, the dissimilarity between the actual and modeled received signal becomes large at the scanning point where significant reflection from the cross bar reaches to the sensor. Therefore, near the cross bar, the propagation time of the reflected signal from the inspected bar cannot be obtained accurately.

Consequently, the minimum distance between two successive cross bars being about 120mm, the reliable propagation time variation only in the non-interfered region becomes too short to accurately estimate the knot’s pitch using a Kalman filter and the maximum likelihood method.

Therefore, in our new method, we propose to analyze the variation of the propagation times along the inspected bar taking into account of the presence of the cross bars positively. That is, in our new method, we first locate the region of interference by the cross bars along the scanning line.

This is performed by observing the optimum pattern matching angle obtained at each scanning point along the scanning line. The optimum matching angle represents the similarity between the actual and the modeled received signals. The smaller the angle is, the better the similarity. It is easily comprehensible that the optimum matching angles obtained at the interfered parts of the inspected bar are larger than those at other parts, i.e. non-interfered parts. So, we utilize the variation of the optimum matching angles to distinguish between the reliable observations from the unreliable ones. We must deliberately avoid the use of the obtained propagation times on those interfered regions for the analysis of the variation of the propagation times to measure the pitch of the knots.

We show next the Kalman filter \([3]\) which we use to make a likelihood to measure the pitch.

\[
\hat{\mathbf{x}}_{k|k-1} = F\hat{\mathbf{x}}_{k-1|k-1} + \mathbf{v}_k \quad \text{(5)}
\]

\[
\mathbf{y}_k = \mathbf{y}_k - H\hat{\mathbf{x}}_{k|k-1} \quad \text{(6)}
\]

\[
P_{k|k-1} = FP_{k-1|k-1}F^T + W \quad \text{(7)}
\]

\[
P_{k|k} = P_{k|k-1} - K_kH^T P_{k|k-1} \quad \text{(8)}
\]

where

\[
K_k = P_{k|k-1}H^T \Lambda_k^{-1} \quad \text{(9)}
\]

\[
\Lambda_k = HP_{k|k-1}H^T + V_k \quad \text{(10)}
\]

Here, the symbols stand for the following:

![Fig. 1 Mesh arrangement of the reinforcing bars in real structures (over view).](Image)
parts will be presented later in the section of experiment.

curately.

propagation time variations to measure the true knot’s pitch ac-

words, through this procedure we can organically combine the

along the scanning line crossing over the cross bars. In other

reliable variations of the mean-subtracted propagation times

lation values in that region.

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above and then multiply it with a significantly larger value of

value of the mean-subtracted unreliable propagation times as

observation noise in that region, we recommend to calculate the

propagation model. So, to define the standard deviation of the

actual propagation time and the measurement noise, caused by

propagation time at this region consists of the variations of the

of the mean-subtracted propagation times in the non-interfered

This is because the variation of the mean-subtracted propagation

time at this region consists of the variations of the

propagation model. So, to define the standard deviation of the

observation noise variance is smaller than the deviation of the variation

interfered region. It is reasonable to assume that the observa-

Note that the observation noise variance is that for the mean-

subtracted propagation time. To execute the Kalman filter, we

have to assign a value to \( V_k \). Since the reliability of the vari-

ation is different depending on the interfered and non-interfered

parts, it is reasonable to assign different values to the \( V_k \) in each

of the individual regions.

We first consider how to assign a value to the \( V_k \) in the non-

interfered region. It is reasonable to assume that the observation

noise variance is smaller than the deviation of the variation of

the mean-subtracted propagation times in the non-interfered

region. This is because the variation of the mean-subtracted propagation

time at this region consists of the variations of the actual propagation

time and the measurement noise, caused by the measurement error of the

propagation times by the signal propagation model. So, to define the standard deviation of the

observation noise in that region, we recommend to calculate the effective value (i.e. root mean square) of the mean-subtracted propagation times and then multiply the effective value with a multiplying factor (MF) less than 1.

On the other hand, for the interfered region, we must avoid using the unreliable variation of the mean-subtracted propagation times. To discard those unreliable propagation times of the interfered regions, we propose assigning significantly larger value of \( V_k \), since assignment of the larger value of \( V_k \) in Kalman filter implies less reliance on the observed data [5]. Therefore, on the interfered region, we calculate the effective value of the mean-subtracted unreliable propagation times as above and then multiply it with a significantly larger value of MF (MF >> 1) to reject the influence of the unreliable observation values in that region.

By adopting this procedure we can selectively reject the un-

reliable variations of the mean-subtracted propagation times without breaking the continuity of the periodic location of knots along the scanning line crossing over the cross bars. In other words, through this procedure we can organically combine the several isolated patches of the non-interfered mean-subtracted propagation time variations to measure the true knot’s pitch accurately.

Concrete values of MF’s for the interfered and non-interfered parts will be presented later in the section of experiment.

4. Experiment

4.1 The Experiment Condition

The EMW radar used is the type NJJ-95A Handy Search (manufactured by Japan Radio Co. Ltd.). The specifications of the radar are: central frequency 800 MHz, sampling period \( \Delta T = 0.04 \text{ ns} \), and scanning pitch \( \Delta L = 3 \text{ mm} \).

To demonstrate the validity of our new method we experimented on a wall of a reinforced concrete structure. Figure 2 shows the section of the inspected wall. The inspected bar is of D13 type and is at a depth of about 80mm from the concrete surface. The alignment of the D10 types of cross bars is below the inspected bar as shown in the figure. According to JIS standard [6], the allowable range of knot’s pitch for D13 type bar is from 6.7mm to 8.9mm.

The radar was used to scan along the length of the deformed inspected bar while being lifted off from the concrete surface by 10mm. The introduction of lift off of the radar during the scanning was to minimize the frequency of simultaneous re-

gection of reflections both from the knot and from the base of the inspected bar [4].

In this experiment the total distance from the start to the stop of the scanning was 723mm. From the B-mode image in Fig. 3, we observe the presence of 3 complete hyperbolic patterns within the scanning distance. The hyperbolic pattern represents the characteristic pattern of a cylindrical buried ob-

ject, provided that the direction of scanning is perpendicular to the length of the cylindrical object [1]. Thus we can find three bars orthogonally crossing the inspected bar. Moreover, from the location of the apex of a hyperbolic pattern the location of the cylindrical object can also be recognized. From the patterns, the locations of the centers of the cross bars were ob-
tained at scanning distances 225, 438 and 618mm respectively. But unfortunately, we can observe quite no information on the periodicity of the knot’s pitch from the B-mode image.

4.2 The Analysis Result by the New Method

At each scanning point, the propagation time of the EMW from the inspected bar was obtained by our previous methods [3],[4]. Figure 4 shows the variation of the propagation times, while Fig. 5 shows the varying optimum matching angles along the scanning distance. From the figure, we observe that the optimum matching angles at the scanning points near the position of the cross bars are comparatively large, as we expected.

Fig. 2 Arrangement of the inspected bar and cross bars in a reinforced concrete structure (sectional view).

Fig. 3 B-mode image of the received EMW signal.
Now, we are required to separate the reliable variations of the propagation times from the unreliable ones influenced by the cross bars. Here, we adopt the angle $14.5$ degree as the threshold value, which is merely the mean of the maximum and the minimum optimum matching angles. The scanning points where the optimum matching angles lie below the threshold value are considered to be less affected by the reflection from the cross bars. If we lower the threshold, the number of available observations becomes smaller and thus a much larger scanning length is needed for an accurate estimation of the knot’s pitch.

Figure 6 shows the propagation times after removing the moving average of the propagation times using 7-point moving average method [4]. Here, the shaded parts of the variation represent the portions where the effects of the cross bars are significant, i.e. the unreliable observations, while the non-shaded parts represent the reliable observations. This is easily understood by observing Fig. 5.

Next we calculate the effective value of the mean-subtracted propagation times obtained at the scanning points of each of the reliable and unreliable parts separately. For reference, we try to multiply the effective values of the reliable and unreliable regions by MF equal to 0.5 and 30 respectively to get the standard deviation of observation noise. When we apply our new method to the data window of the width 723mm, we get the likelihood function as shown in Fig. 7. From Fig. 7 we observe that the maximum of the likelihood function appears in the region for D13 (i.e. the true type of the inspected bar). However, when the width of the data window is short, even with our new method we cannot get an accurate estimation of the knot’s pitch (consequently, the diameter of the bar). This is because the main concept of our new method is to make use of a long series of reliable observation data organically, although the clusters of reliable observations are skipped and isolated from each other by cross bars.

We also applied our new method to the variation of propagation times obtained from another scan of the same specimen. In this case, too, we succeeded to measure the true diameter of the bar, although the details are omitted.

### 4.3 The Optimal Arrangement of the Observation Noise Variance

We multiplied the effective values of the mean-subtracted propagation times in reliable and unreliable parts by the respective MF to calculate the corresponding standard deviations of the observation noises on those parts. When we changed the MF, we found that selecting the MFs within the range 0.4 to 0.8 for the reliable parts and greater than 10 for the unreliable parts ensured obtaining accurate measurement. Figure 8 shows the acceptable range of the MFs for both the reliable and unreliable parts.

### 4.4 Evaluation of the New Method

We now evaluate our new method by comparing with the results by our previous method which adopted a lift-off of the radar [4]. Figure 9 shows the likelihood function obtained by applying our previous method to the observed variation in Fig. 6. Here the width of the data window (i.e. the scanning distance) is taken as 723mm, i.e., the same data window on which we successfully applied our new method. But, to get the standard deviation of the observation noise, we calculate the...
effective value of the mean-subtracted propagation times obtained along the whole of the scanning length and multiplied it by 0.5. That is, we have assigned equal importance of the reliable and unreliable parts in the process of measurement, without the consideration of the presence of the cross bars.

Figure 9 shows that the maximum of the likelihood function lies in the wrong region of knot’s pitch. So, although the scanning distance is the same as that used in the new method, the previous method fails to correctly estimate the diameter for not considering the effective effect of cross bars.

We also analyzed the variation of the propagation times obtained at each of the reliable parts separately, but the measured knot’s pitch did not lie within the right region of knot’s pitch for the inspected D13 type of bar in any of the cases. For example, Fig. 10 shows the likelihood function obtained for the first reliable part in Fig. 6, where the maximum falls into the region for D19 type bar (i.e. the wrong region).

Since the information seems to be less within only one isolated reliable part, we next tried to sum up the likelihoods obtained from the reliable parts to improve the reliability. But in this case too, we could not measure the diameter of the bar accurately. Figure 11 shows the summation of the likelihoods of the first 2, 3 and 4 reliable parts respectively. We can see that the maximum of the likelihood lies in a different region of diameter than the actual one in each of the three cases.

Comparing the results of the authors’ previous methods with the new one, we can say that our new method is quite effective. This is because the new method can organically combine the observations of the isolated reliable regions. In other words, the method can extract the periodicity of the knot’s pitch accurately by observing the knot’s location over a long distance although several knots are skipped on the way.

According to JIS, the minimum and maximum allowable nominal diameters of deformed bars are 4.23mm (D4 type) and 50.8mm (D51 type) respectively. The maximum value of average knot’s pitch of these bars are 3mm and 35.6mm respectively [6]. Using our new method with the EMW radar of 3mm scanning pitch, it is at least possible to measure the diameter equal to or greater than D13 type of bar, as has been confirmed through experiment. However, if the scanning pitch of the radar can be made smaller, our method can still be applied for the bar having diameter less than that of D13 type of bar.

5. Conclusions

In order to measure the diameter of the reinforcing bars in real concrete structures, where the bars are arranged in mesh pattern, we proposed a new method. From experiments it was proved that the presence of the cross bars did not hinder the measurement process since the new method allowed us to avoid the influence of the cross bars as well as assisted us to combine the uncorrupted propagation time variations within two consecutive cross bars to obtain an accurate information on the diameter of the inspected bar. Finally, the effectiveness of the new method was verified and compared with the authors’ previous method.

References


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