A Method for Remote Monitoring of Structural Health Based on the Nonlinear Phenomenon in Dynamic Response of Damaged Structures

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Abstract

A new method for remote crack monitoring, based on the breathing crack phenomenon and wavelet transform, is proposed. During vibration, edges of a crack come into and out of contact which causes non-linear effects in the response of a structure, due to changes in the structural stiffness, as the crack opens and closes. Wavelet Transform is applied to detect such nonlinear effects in the response signals of the structure. The results of numerical studies obtained from the FE analysis and experimental tests of simple specimens promise a practical technique for remote structural health monitoring.

Keywords: Breathing crack, wavelet transform, structural health monitoring, crack detection.

I. INTRODUCTION

The dynamic characteristics of a cracked structure and an intact structure are, in principle, different. The reason for this difference is the change in stiffness when a structure is cracked. During vibration a crack will open and close in time due to an externally applied loading. This phenomenon is known as the breathing process of the crack. During the breathing process the two edges of the crack come into and out of contact, thus the stiffness in the crack region may increase or decrease. This will cause changes in dynamic response of the cracked element which would be useful for detection of cracks [10].

The influences of the breathing crack phenomenon on dynamic characteristics of fatigue cracked structures have been widely studied. The non-linear behaviour of the longitudinal free and forced vibration of structures was investigated using direct numerical integration [1,3,4]. In other researches, it has been found that the relative increase in natural frequencies due to the crack closing is much smaller than the decrease due to the crack opening [2, 6]. Effects of closure of cracks on dynamic responses of a cracked cantilever beam were studied using successive modal transformations [8]. Zastrau [12], used the finite element method to study the steady state responses of a simply supported beam with multiple closing cracks. Non-linear distortions of the dynamics due to fatigue damage were investigated by V.V. Matveev and A.P. Bovsunovsky [9]. Methods based on change in resonant frequency are difficult to apply because the minute changes in frequency are difficult to measure. Even where these methods can be applied they cannot locate the position of the crack or determine the depth of the crack.

In the last two decades, wavelet transform has emerged as a fast-evolving mathematical and signal processing tool for many fields. The important property of wavelet transform is its capability to analyse signals locally. The position of the crack of an open cracked beam was found by applying the wavelet transform to analyse the deflection of the beam [11]. Douka et al [5] presented a method for crack identification in plates based on wavelet analysis. The position of the crack is determined by the sudden change in the spatial variation of the transformed displacement response. Hong et al [7] investigated the effectiveness of the continuous wavelet transform in terms of its capability to estimate the Lipschitz exponent as a measure of structural damage. The above researches are mode shape based and therefore impractical because of the requirement for large amounts of accurate data. A combination method of using breathing crack phenomenon and wavelet transform for local monitoring was proposed by this paper's authors [10]. The existence of a crack and the crack depth were determined by using wavelet transform to detect the nonlinearity of strain time history caused by the breathing crack during vibration. The position of the crack was identified by the position of the distortion in the phase shift distribution across the crack position. However, in this method, the crack site was assumed to be known or predicted.

In the studies reviewed, monitoring of responses is carried out locally (i.e. near the site of the crack) in many of the cases. In these cases, in order to detect the crack, the crack site must be known or response signals must be measured at many points on the monitored structure. However, local monitoring is difficult in practice especially if the site of a crack cannot be predicted. Moreover, for complex structures, the measurement of the response signals at a large number of points is simply impractical. Remote monitoring would therefore appear to be a more practical option. This refers to monitoring the structural response at a remote point from the site of a fatigue crack.

This study is aimed at on-line health monitoring of structures where the site of a crack is unknown or unpredicted. The structural response to be used in this method is acceleration because it can be easily measured in practice and it can be measured at any convenient position since the breathing crack influences the acceleration signal over most of the monitored structure. The theoretical background of the dynamics of a vibrating beam with a breathing crack was described in a previous paper [10] along with the application of wavelet transform in crack detection. The current paper will present the results of a numerical and experimental study to establish a technique for remote monitoring of fatigue cracks.

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II. NUMERICAL STUDIES

A.. Simulation of cracked beam vibration response

In order to analyse the dynamic response of a cracked beam, ALGOR - finite element software has been used. The crack is described as shown in Figure 1. In this model the crack consists of two close edges which may come in and out of contact during vibration. It is expected that when the load is a sinusoidal function the acceleration response function should not be purely sinusoidal but it should be distorted due to the non-linear effects of the crack opening and closing.
Seven levels of the crack from zero to 60% have been investigated. These seven cases are numbered as in Table 1.

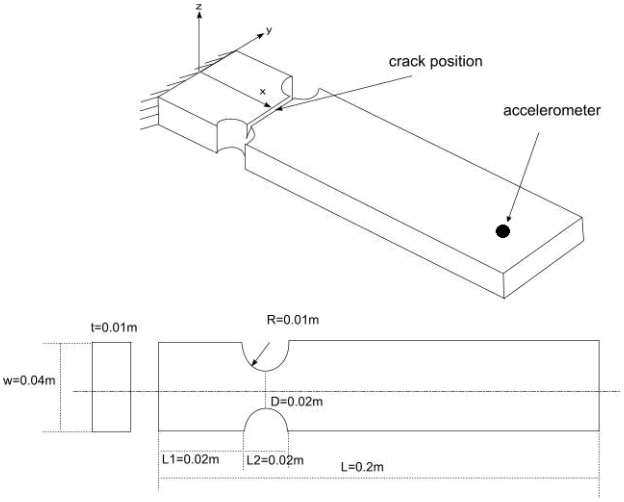

Figure 1: A cantilever beam with a crack

Table 1. Seven cases with cracks of varying depths at crack position x=30 mm

Case	1	2	3	4	5	6	7
Crack depth (%)	0	10	20	30	40	50	60

B. Detection of crack existence and crack depth using wavelet transforms

1) Detection of crack existence

The acceleration signals are measured at the free end of the beam. Figures 2 to 4 present the normalized acceleration-time history and its continuous wavelet transform for each of three different levels of the crack. In these figures, the upper graph is the acceleration signal and the lower graph is its wavelet transform. Figure 2 indicates no discontinuity in the wavelet transform when the beam is intact. Figures 3 and 4 show increasing levels of discontinuity in the wavelet transform of the acceleration signal as crack depth increases, clearly indicating distortions in the acceleration signals at moments that the crack opens or closes.

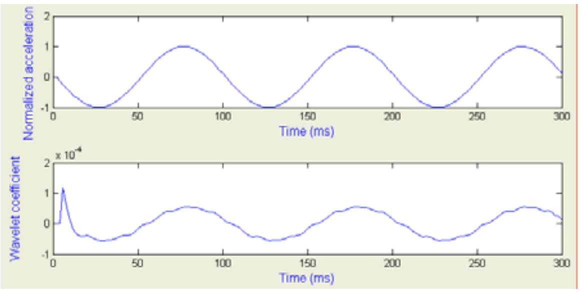

Figure 2: Crack depth is 0%

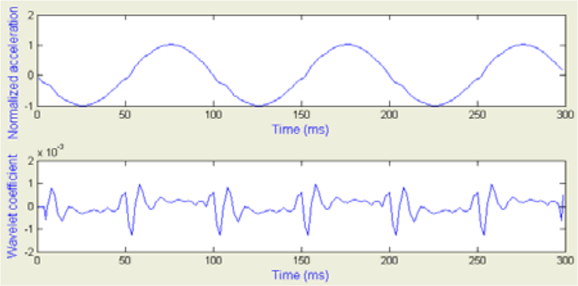

Figure 3: Crack depth is 20%

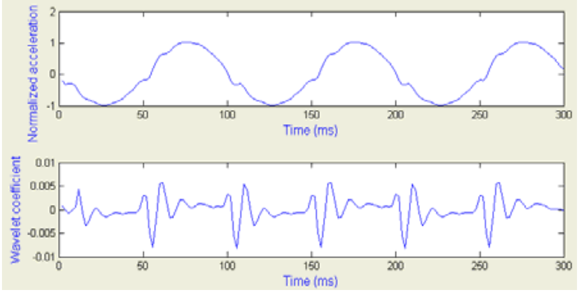

Figure 4: Crack depth is 40%

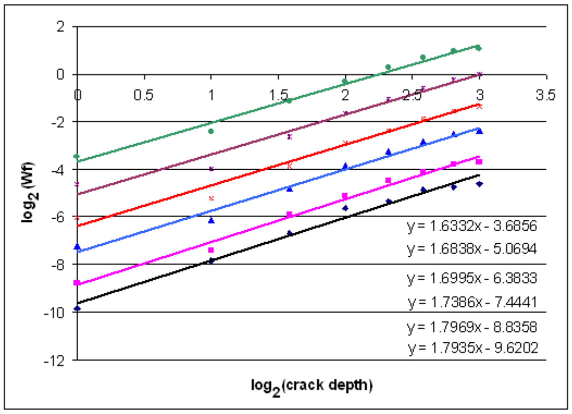

Figure 5. Maxima lines versus scale for four levels of crack: 10% to 60%

2) Detection of crack depth

The crack depth is determined using the modulus maxima lines of the wavelet transform. Equation (1) describes the relationship between crack depth and the coefficients of wavelet transform [7].

$$\log_2(|Wf(a,b)|) \le \log_2 A + h\log_2(a) \quad (1)$$

where wf(a,b) are wavelet coefficients, a is scale, b is position, A is intercept of the modulus maxima line and h is Lipschitz exponent of the wavelet transform.

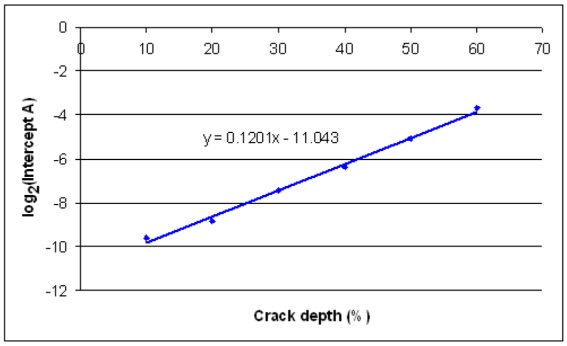

Figure 6: Intensity factor versus crack depth

Figure 5 shows that when the Lipschitz exponent h is fixed, only the intercept A changes when the crack depth changes. Thus, each parallel line is distinguished by its intercept (A). This intercept increases when crack depth increases. Because of this, the intercept (A) can be considered as an intensity factor which relates the extent of the fatigue crack to the wavelet coefficients. Establishing a graph of intercept (A) versus crack depth from Figure 5, a relationship between intercept (A) (or intensity factor) and crack depth is obtained as shown in Figure 6. It can be seen that this relationship is a linear in semi-log plot.

C. Detection of crack position using signal ratio

For a structure with a crack, it is considered that the structure consists of two different sections joined at the crack position. Detection of the crack position is based on the change in the stiffness of the cross-section at the crack when it breathes. During vibration, the signal ratio of normalized acceleration between two points on the same section of the structure is expected to have little or no distortion, whereas the signal ratio between two points on the two different sections, either side of the crack, should have more significant distortion due to the change in cross-sectional stiffness at the crack as the crack opens and closes.

The signal ratio between two points can be calculated as follows: $h(t) = \dfrac{f_1(t)}{f_2(t)}$ (2)

where h(t) is the signal ratio; $f_1(t)$ is the response signal at point 1 and $f_2(t)$ is the response signal at point 2.

Using data from FE analysis, seven levels of crack depth (see Table 1) are applied to investigate the influence of the position of the crack on the signal ratio between different points. In each case, five points along the specimen are selected to measure the signal ratio as can be seen in Table 2 and Figure 7. Signal ratios are calculated between point 5 (fixed) and the other four points 1, 2, 3, 4. The crack position is at x=30mm, i.e. in between point 1 and point 2.

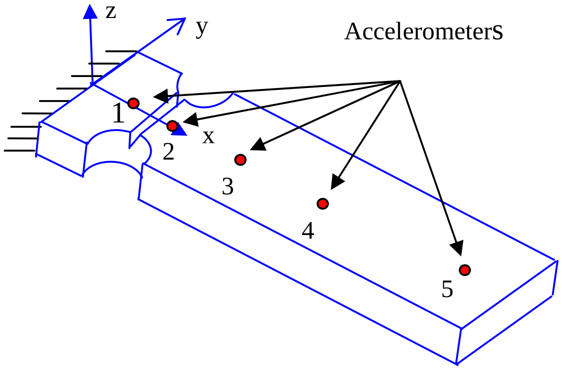

Figure 7: Positions of five measurement points along the specimen

Table 2: Positions of measurement points.

Point	1	2	3	4	5
x (mm)	13	36	47	108	170

Figures 8 to 10 present signal ratios between these five points along the specimen for three different levels of the crack.

The signal ratios in Figs. 8 are constant and equal to 1 for the intact specimen. This implies that when there is no crack, there is no factor to influence the transmission of vibration signals along the specimen. Figures 9 and 10 show the signal ratios for the specimen with the crack depth of 30% and 60%.

As expected, for each level of the crack, the signal ratios between points 2, 3, 4 and point 5 on the same section are quite similar with small levels of distortion presented by peaks in the signal ratios while the signal ratios between two points on different sections, i.e. between point 1 on section I and point 5 on section II, show larger levels of distortion compared with signal ratios of points on section II. The signal ratios from point 1 to point 4 show that there are significant changes in the signal ratio when it passes from point 1 to point 2. This means that the crack position is in the area between point 1 and point 2 as expected.

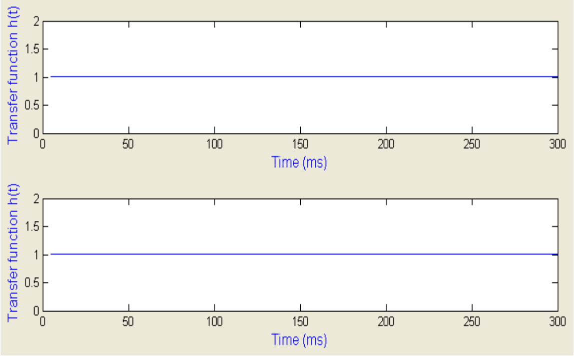

Figure 8: Signal ratio between points 1, 2 and point 5 for crack depth of 0%

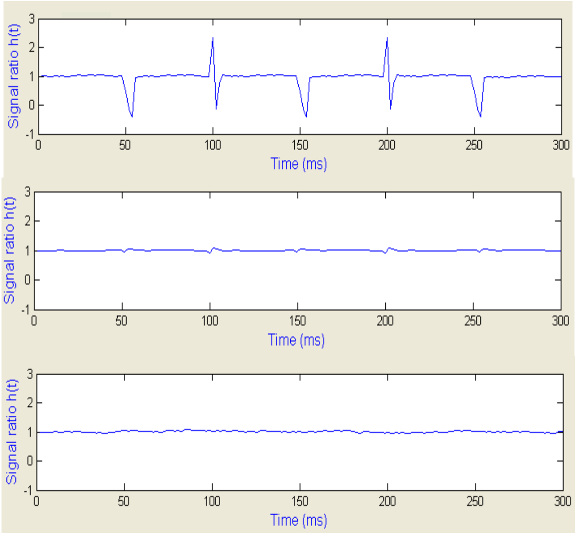

Figure 9: Signal ratio between points 1, 2, 4 and point 5 for crack depth of 30%

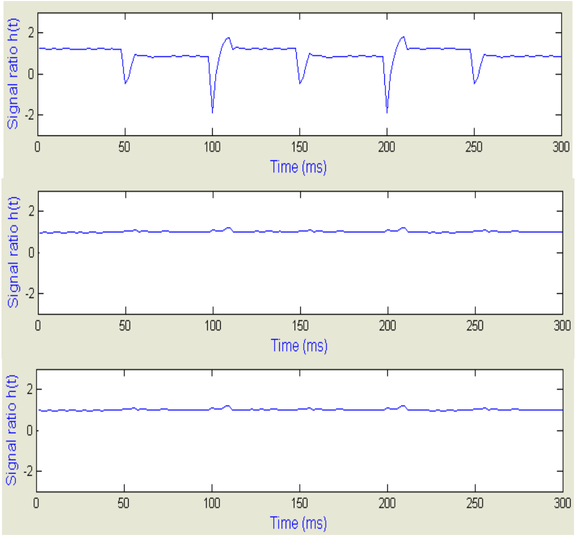

Figure 10: Signal ratio between points 1, 2, 4 and point 5 for crack depth of 60%

III. EXPERIMENTAL RESULTS

Having developed the remote monitoring method based on the combination of breathing crack and wavelet transform as described in the previous sections, it is very important to demonstrate its practical application for structural health monitoring. For this purpose, experimental tests have been carried out to detect and monitor fatigue cracks in beam structures similar to that used in the numerical studies. Structural response was monitored in the form of acceleration response signals from which the health of the structure could be determined at various stages of fatigue damage.

A. Detection of crack existence

Figures 11 to 14 present normalized acceleration-time histories and their wavelet transforms for four cases taken at different stages during the fatigue test on the specimen. They show increasing levels of discontinuity in the wavelet transform of the acceleration signal as crack depth increases, clearly indicating distortions in the acceleration signals at moments that the crack opens or closes. This indicates that the experimental result of crack detection using acceleration is in agreement with the FE analysis result.

The relationship between intercept (A) (or intensity factor) and crack depth, obtained from the modulus maxima lines for the different crack depths is shown in Figure 15. It shows a linear relationship between the intercept A and crack depth in a semi-log plot in a similar manner to the numerical study results.

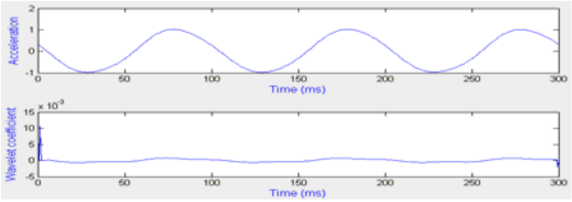

Figure 11: Crack depth is 0%

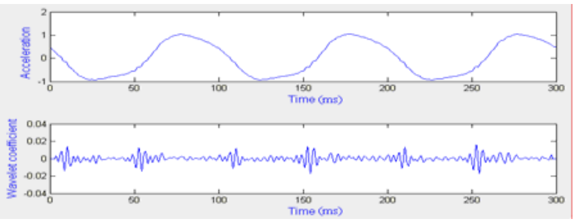

Figure 12: Crack depth is 20.1%

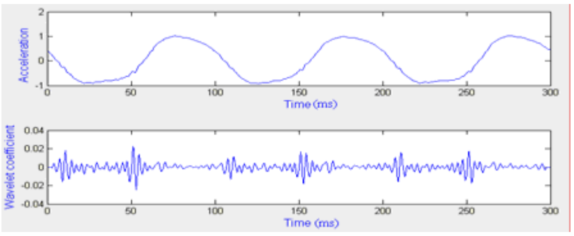

Figure 13: Crack depth is 41.5%

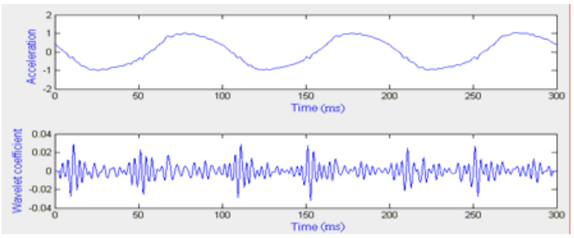

Figure 14: Crack depth is 60.2%

B. Detection of crack depth

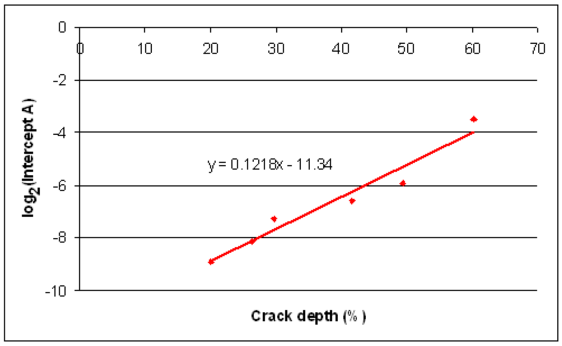

Figure 15: Intensity factor versus crack depth

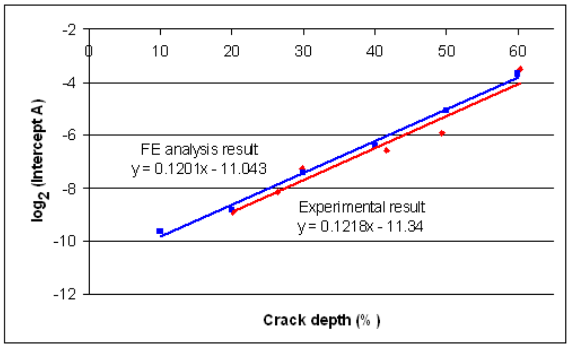

Figure 16: Relationship between crack depth and intercept: the red line is the experimental result; the blue line is the FE analysis result.

Figure 16 presents the comparison between experimental and FE analysis results of the relationship between the intercept A and the crack depth. The figure shows close agreement between the numerical and experimental results. However there are minor discrepancies. The Lipschitz exponent from the experiment is 1.86 and is different from FEA where the value of Lipschitz is 1.72. This can be explained by the fact that in the FE analysis the crack is modelled as surface to surface contact without rebounding, sticking and sliding phenomena which may occur in practice. Moreover, the surfaces of two edges of crack are not as smooth as modeled in FE analysis. Background noise may also be a contributory factor to the difference between numerical and experimental results.

C. Detection of crack position

To measure the signal ratio, a configuration of five accelerometers as in Figure 8 is used. Figures 17 to 19 show signal ratios between point 5 and the other four points 1, 2, 3, and 4 for three cases when the crack depth is from 0% to 59.3%. These figures show that, for each crack depth greater than 0, the signal ratio has a significant change when it goes across from point 1 to point 2 and then remains nearly the same from point 2 to point 4. This means that the crack is in between point 1 and point 2.

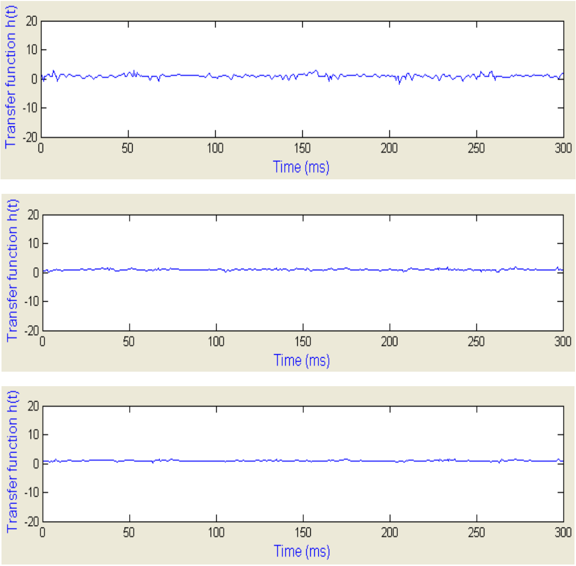

Figure 17: Signal ratio between points 1, 2, 4 and point 5 for crack depth of 0%

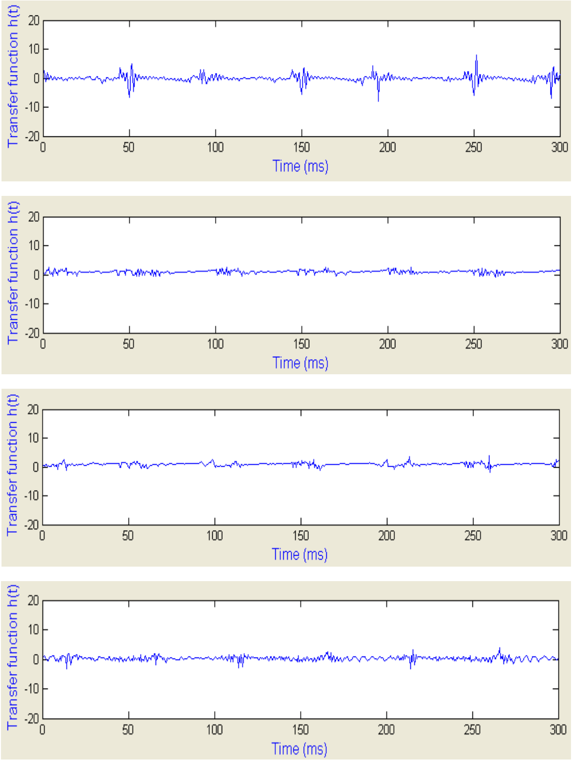

Figure 18: Signal ratio between points 1, 2, 3, 4 and point 5 for crack depth of 20.1%

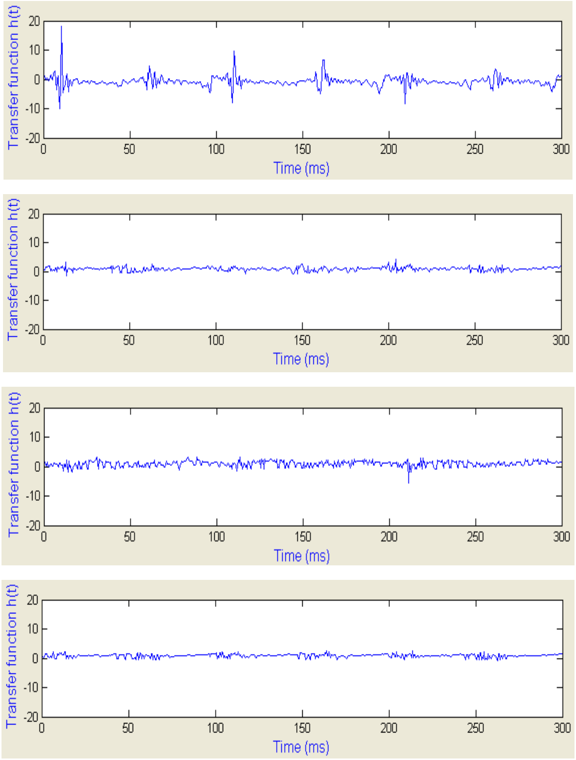

Figure 19: Signal ratio between points 1, 2, 3, 4 and point 5 for crack depth of 59.3%

IV. CONCLUSIONS

A practical method for remote monitoring of fatigue crack has been proposed. In this method, the acceleration response signal is used because it can be easily measured in practice and the acceleration response over most of the monitored structure can be influenced by the breathing crack phenomenon. The method is a development of the authors' previous study based on the combination of breathing crack and wavelet transform to detect the existence of a crack in a structure and the crack depth. A new approach based on signal ratio analysis for detection of crack position is also proposed. Detection of the crack position is based on the significant change in the signal ratio between two points on either side of the crack due to the change in cross-sectional stiffness at the crack as the crack opens and closes.

The method has been demonstrated by a numerical study and a fatigue test on a simple specimen carried out in the laboratory. The appearance of the crack detected from experimental data is in agreement with the result of FE analysis. The relationship between crack depth and the intensity factor (A) based on experimental data is established as a basis to estimate the crack depth. The ability of the new approach to detect of crack position, based on signal ratio, has been established in the numerical study and confirmed experimentally.

In conclusion, the new method is adequate to apply for detection and remote monitoring of a crack in the test specimen. The advantages of this technique are that it is capable of being implemented in a practical manner since the acceleration time history signal can be easily measured in practice. Furthermore, the use of acceleration signal facilitates remote monitoring of the structure for fatigue cracks when the crack site is unknown or unpredicted. This paper has established the proposed technique for remote structural health monitoring using a simple structure and further studies on real components under real test conditions are proposed to further validate the method.

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