# MONITORING OF FATIGUE CRACK PROPAGATION OF ENGINEERING STRUCTURES USING TIME REVERSAL METHOD

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**Keywords**: *guided waves, fatigue crack, time reversal method, imaging approach*

## 1 Abstract

In this study, a technology based on ultrasonic guided waves for monitoring fatigue crack in metallic structures is demonstrated in which two different sensor networks including eight and six piezoceramic (PZT) transducers are employed respectively for exciting and acquiring guided wave signals. One network is arranged for detecting the location of fatigue crack; while the other one is disposed on account of fatigue crack propagation monitoring using a time reversal method. By applying cyclic fatigue load, a fatigue crack is introduced into a 5 mm-thick steel plate by four steps mounting up in a steady graded series from 7 mm to 27 mm. It is inevitable that after a succession of fatigue tests in great intensity, the PZT transducers indicate a discrepancy in the properties of signal excitation and acquisition due to mechanical impact no matter on PZTs or bonding layers. Evidently, application of a reference-free method is significant for monitoring fatigue crack by way of averting exterior adverse impact. That is the reason why the time reversal method is involved in this study. Results of the study show that the time reversal method combined with probability-based damage imaging approach according to time of flight and coefficient are suitable for estimating the presence and propagation of fatigue crack in metallic structures.

## 2 Introduction

Detection and monitoring of small failures especially fatigue cracks in engineering structures of dissimilar geometry are very difficult problems. Recently, heterogeneous detecting technologies including contact and non-contact sensing methods were examined with a view to locate or monitor fatigue cracks in metallic or non-metallic structures.

The development of ultrasonic techniques using PZT transducers takes the contact sensing method for crack detection into an advanced stage, and Lamb wave-based method in view of this technique has been extensively investigated for failure identification in infrastructures on account of the attractive features of Lamb waves [1-3]. However, the Lamb wave-based method is related to a major drawback if using traditional signal processing and interpretation techniques which require baseline measurements. The measure parameters can change due to applied cyclic loading or bad coupling between the PZT transducers and structure. While non-contact approaches such as laser-based techniques were also developed recently and effectively employed for fatigue crack detection [4, 5]. Although this kind of method can avoid baseline measurements and save some complex data interpretation process, the setup of delicate equipments for data acquisition makes it hard for real-time defect monitoring.

Synthetically, any developments that can meet the challenge of fatigue crack detection are thus very attractive for real engineering applications. Applications of Time Reversal Method (TRM) based on Lamb-wave approach for structural health monitoring are not new and include research work on damage detection in metallic [6] and composite [7] structures. The effectiveness and robustness, especially characteristic of baseline free of TRM makes it feasible for fatigue crack monitoring. This paper describes the experimental work using Lamb waves which involves two different PZT sensor networks for the detection and monitoring of a fatigue crack in a steel plate of 5mm in thickness.

## 3 Fatigue Crack Detection

### 3.1 Fatigue Test and Guided Wave Generation by PZT Transducers

Figure 1 shows a steel plate of 600mm×200mm×5mm in size was clamped in the 250kN MTS fatigue-testing machine in the force-controlled mode via a MTS Load Unit Controller. The material properties of the specimen are detailed in our previous studies [8]. In order to initiate a fatigue crack, an artificial notch of 5mm×5mm was induced in one longer edge of the specimen. The fatigue test was implemented to initiate and grow a fatigue crack along the notch. The dynamic cyclic loading of 5kN-50kN was adopted in the fatigue test. The length of the fatigue crack was firstly generated to 7mm. The crack was located along the sharp angle of the notch as shown in Fig. 2.

As shown in Fig. 3, six circular PZT transducers of sensor network 1 and six same transducers with the dimensions of 10 mm in diameter and 1 mm in thickness were surface-mounted to the plate to serve as either actuators or sensors. MATLAB® software was used to generate the excitation signals and the signals were fulfilled using a system developed on the VXI platform, consisting mainly of an arbitrary signal generator (Agilent_ E1441), signal amplifier (PiezoSys_ EPA-104), signal conditioner (Agilent_ E3242A), and signal digitizer (Agilent_E1437A). A 5-cycle sinusoidal toneburst (60V peak-to-peak) enclosed in a Hanning window at a central frequency of 200 kHz was generated and acquired at a sampling rate of 20.48 MHz. When a PZT transducer was activated, the rest were regarded as sensors to monitor propagations of guided waves in the steel plate.

### 3.2 Identification of Fatigue Crack by Probability-based Imaging Approach

The Lamb wave signals obtained from sensing paths were captured when the structure was in the pristine condition and after the introduction of fatigue crack. Wavelet analysis can be used to transfer the guided-wave signals from time domain into time-frequency domain. In this study, continuous wavelet transform (CWT) and Hilbert transform (HT) were applied for processing of the acquired signals. For one typical sensing path P4-P7, the HT coefficients of processed wave signals at reference and damage states are illustrated in Fig.4. The first maximal changes in arrival time and amplitude (FMC) of reflected signals can be observed and used for locating fatigue crack for this sensing path, which means that the reflecting sensing path was seriously impaired by the fatigue crack.

With the FMC obtained from experiment, effort was focused on determining damage presence probabilities (DPPs) of all positions of the steel plate rather than defining exact location of fatigue crack. An imaging algorithm was adopted to represent DPP values which vary within the range of [0, 1] with the two extremes standing for the lowest and highest DPP, i.e., 0% and 100%, respectively, for the steel plate, expressing the result in an intuitional manner. In order to keep consistent with our previous studies and without loss of generality, most of the definitions were inherited except the geometries [9]. On account of the same principle and based on the average value theory, images contributed by all the available paths in the active sensor network were fused to figure out the common estimate of the location of damage, which can be clearly seen from the two-dimensional DPP image. The evaluated location is shown in Fig. 5 at the darkest area and the real location of the fatigue crack tip is illustrated as the black square.

## 4 Fatigue Crack Monitoring

After the location of fatigue crack was identified in the first estimation, the steel plate with 7mm fatigue crack was considered to be monitored by PZT sensor network 2 (shown in Fig.2.). It can be clearly seen that after millions of cycles, the signals change a lot according to previous state. In order to obtain more accurate results, baseline-free methodology has to be adopted for subsequent analysis.

### 4.1 TRM-based Signal Interpretation

TRM combined with Lamb wave approach (TRM&L) has been established [6, 7], but the study of the TRM&L for fatigue crack monitoring has never been mentioned. The TRM has been formulated in the frequency domain incorporating the PZT transducers used for excitation and measurement of Lamb waves [10].

The principle of TRM can be explained as follows. An input signal can be firstly rebuilt at a PZT transducer while an output signal recorded at another PZT transducer is retransmitted to the original PZT transducer after being reversed in the time domain as illustrated in Fig. 6 [7]. The specific goal of the research described in this paper is to reconstruct the known excitation signal at the original input location through the TRM based on Lamb waves in order to monitoring the fatigue crack ahead of 7mm length.

### 4.2 Correlation Coefficients Image Approach with the Combination of TRM for Fatigue Crack Monitoring

After the TRM process, finally a series of coefficients can be obtained according to the differences of original required signals and retransmitted signals. For estimating the probability of the propagation of the fatigue crack in the monitoring area, the correlation of two signals offers a clue as to how well the value of one signal can be approximated from the value of the other [11]. In this study, the propagation of the fatigue crack is assumed to be the exclusive explanation for the changes in coefficient by TRM based on Lamb wave signals between the initial state and the states when the crack extended to a certain length. On the basis of this principle, the complexity of structural geometry or boundary condition, especially the adverse effect caused by applied cyclic load would not affect the capability of this probabilistic damage diagnostic algorithm, as these influences are implicitly included in both the reference and present signals. The degree of changes in signals from a certain sensing path before and after crack propagation is introduced will be clearly increased if the sensing path is much closer to the tip of the fatigue crack. It is evident that the correlation coefficients for seriously damage-impaired sensing paths are lower than those for slightly damage-impaired sensing paths. As a result, the damage signatures for individual sensing paths can be calculated by subtracting the corresponding correlation coefficients from 1.0, which can be presented in the uniformly distributed grids of the monitoring area [12].

The results of correlation coefficient-based image according to TRM were illustrated in Fig. 7. Figure 7a represents the state when the fatigue crack is 7mm in length. Subsequent two diagrams (Figs. 7b, c) show the states when the fatigue crack was extended to 17mm and 27mm, respectively. However, it is noteworthy that the estimation could lead to confusing information due to the small distance between two adjacent groups of PZT transducers. By adding the coefficients under different damage conditions together, we can see from Fig. 8 and Table 1 that the sum of coefficients increases with the propagation of fatigue crack from 7mm to 27mm, which demonstrates that the lowest sensing path of P4-P12 is significantly affected due to the fatigue crack propagation.

## 5 Conclusions

Probabilistic damage diagnostic algorithms based on FMC and correlation analysis were validated experimentally for a steel plate with an artificially introduced fatigue crack. The algorithm is independent of the analysis of detailed information of Lamb wave signals from individual sensing paths. The location of the fatigue crack firstly detected using FMC-based image algorithm and then the degree of changes in signals corresponding to the propagation of the fatigue crack was calibrated by correlation coefficients extracted from TRM**,** using the captured signals and the reconstructed signals, respectively. Estimations of three fatigue crack lengths were performed using both the wave signals captured at states of the 7mm, 17mm and 27mm fatigue crack. The identified locations of fatigue crack and monitoring of fatigue crack propagation agreed well with the actual situations, demonstrating the algorithm with the applications of FMC and TRM was capable of locating and monitoring fatigue crack in plate-like structures.

## Acknowledgement

The authors are grateful for the support received from Research Grant Council of the Hong Kong Special Administration Region and National Natural Science Foundation of China (grants: PolyU5333/07E and N_PolyU532/10) and The Hong Kong Polytechnic University (grants: G-U204 and 1-BBZN).

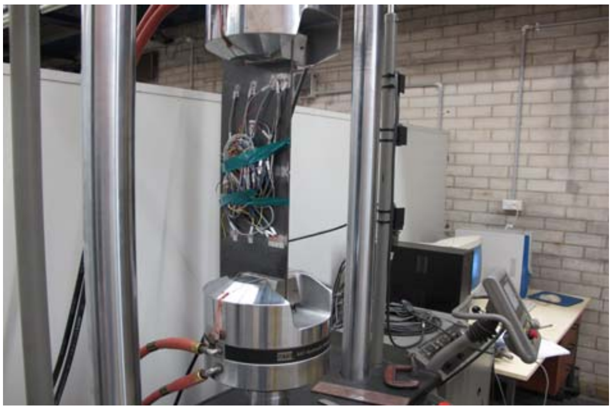


Fig.1. Specimen used in experiments.

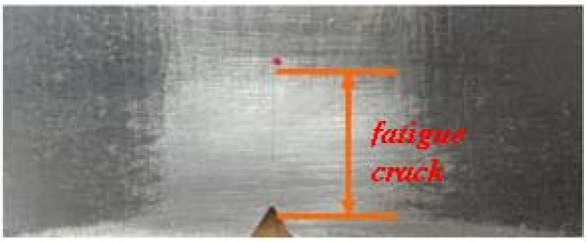



Fig.2. Zoom view of fatigue crack introduced

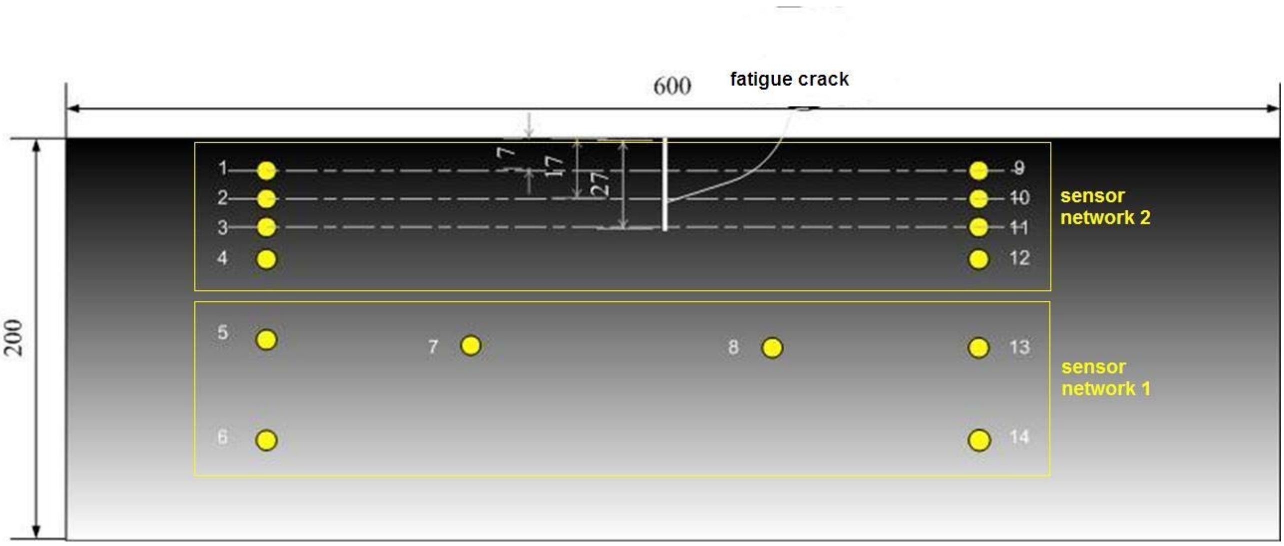



Fig.3. Two PZT sensor networks

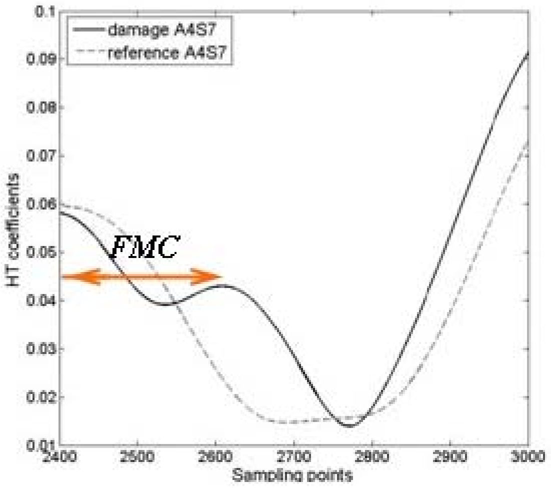



Fig.4. HT coefficients from a typical sensor path P4-P7.

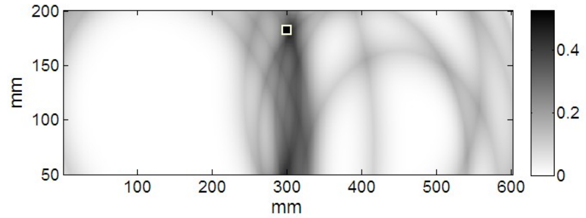



Fig.5. Estimation of fatigue crack location by FMC based DPP.

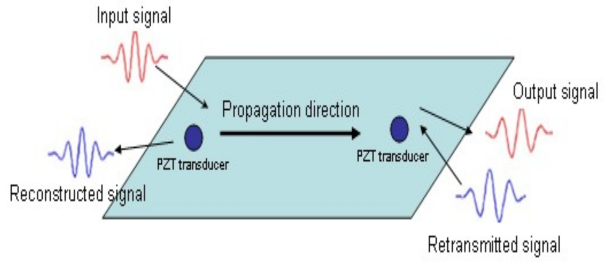
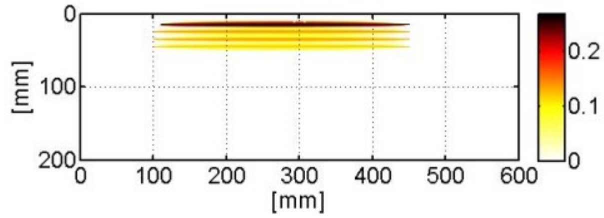
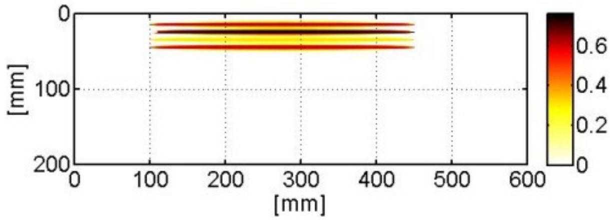


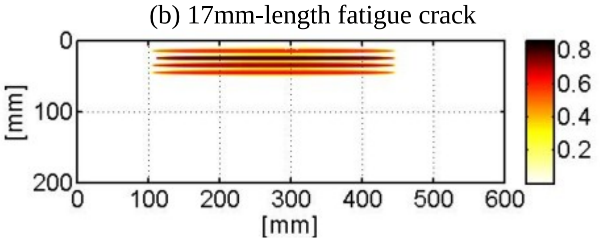

Fig.6. TRM principle.




(a) 7mm-length fatigue crack




(b) 17mm-length fatigue crack




(c) 27mm-length fatigue crack

Fig.7. Fatigue crack monitoring results based on coefficients extracted from TRM

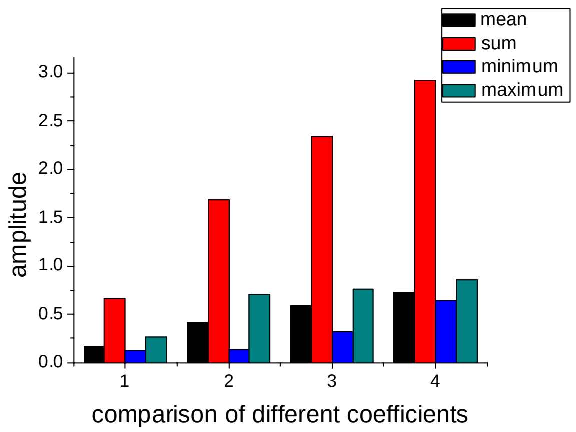



Fig.8. Parameters obtained from TRM coefficients

Table 1. Sum of TRM coefficients with the propagation of fatigue

| Crack length(mm) | 0 | 7 | 17 | 27 |
|---|---|---|---|---|
| Sum | 0.66336 | 1.6823 | 2.33728 | 2.92176 |

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