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Ultrasonic Measurement of Crack Opening Load for Life-Extending Control of Mechanical Structures★

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***Abstract*— This paper develops and validates a technique for real-time measurement of crack tip opening load using ultrasonic sensors and its application to life-extending control of mechanical structures. To experimentally validate the proposed measurement technique, fatigue tests have been conducted in the laboratory environment on center-notched 7075-T6 aluminium alloy specimens. The energy of reflected ultrasonic waves is used to detect crack closure and opening phenomena that lead to real-time measurement of crack opening load. Experimental results are compared with the Newman's crack opening stress model under constant amplitude cyclic loading. A life-extending control scheme is proposed by taking advantage of the real-time information on fatigue damage in mechanical structures.**

I. INTRODUCTION

Fatigue damage is one of the most commonly encountered sources of structural degradation in complex mechanical systems. The literature on fatigue & fracture abounds with a variety of empirical models of fatigue damage propagation. For example, the modified Paris-Erdogan equation [1] describes the fatigue crack growth behavior as

$$\frac{da}{dN} = C\left(\Delta K^{eff}\right)^m \tag{1}$$

where $\Delta K^{eff} = K_{max} - K_o$ is the effective stress intensity factor; K_{max} and K_o are the stress intensity factor corresponding to the peak stress (S_{max}) and crack opening stress (S_o); C and m are constants depend on material properties and specimen geometry. In this context, Elber [2] proposed that cyclic stresses below S_o does not contribute to crack growth due to crack closure. A widely used constitutive equation for crack opening stress has been proposed by Newman [3] for constant-amplitude cyclic loading, which is presented below.

$$S_o/S_{max} = \begin{cases} A_o + A_1 R + A_2 R^2 + A_3 R^3, & R \geq 0 \\ A_o + A_1 R, & -1 \leq R \leq 0 \end{cases} \tag{2}$$

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where R is the stress ratio S_{min}/S_{max} with S_{min} and S_{max} being the minimum and maximum within a stress cycle.

The coefficients A_o, A_1, A_2, and A_3 are given as

$$\begin{aligned} A_0 &= \left(0.825 - 0.34\alpha + 0.05\alpha^2\right) \\ &\quad \left[cos(\pi S_{max}/2S_{flow})\right]^{1/\alpha} \\ A_1 &= (0.415 - 0.071\alpha)\, S_{max}/S_{flow} \\ A_2 &= 1 - A_0 - A_1 - A_3 \\ A_3 &= 2A_0 + A_1 - 1 \end{aligned} \tag{3}$$

where the constraint factor α varies from 1 (plane stress) to 3 (plane strain); and S_{flow} is the average of ultimate strength and yield strength of the material, i.e., $S_{flow} \triangleq (S_{ult} + S_{yield})/2$.

In the current state-of-the-art, accurate measurement of crack opening stress is an area of active research; much efforts have been expended to measure crack opening stress experimentally and develop empirical models for crack opening stresses under varying amplitude loading based on experimental data [4], [5]. The existing methods for measurement of crack opening stress are broadly divided in two areas: (i) compliance, and (ii) crack propagation, which have their own limitations and advantages.

The compliance technique is based on mechanical response of the specimen in the sense that compliance of a fatigue-damaged structure is altered if a portion of the cracked surface closes allowing load transfer to occur through support. A major shortcoming of this technique is that the measured crack opening stress is sensitive to the location of displacement gages and compliance curves obtained from remote clip gages are too insensitive to detect the near crack tip closure. Vasudevan and Sadananda [6] pointed out that the compliance technique overestimates crack opening stress for measuring asperity-induced crack closure while, in some cases, it may underestimate the crack opening stress.

The crack propagation method is built upon the fact that crack propagates only when effective stress intensity is greater than a threshold value of stress intensity. A low-amplitude load is applied on cracked specimen to measure crack opening stress. By keeping S^{min} constant, S^{max} is increased slowly until the crack propagation occurs; the resulting stress range yields the measure of crack opening stress [7]. Since this procedure needs very precise instrumentation and may not be able to capture the dynamic behavior of fatigue crack growth, it is only suitable for offline evaluation of crack opening stress. Another limitation of this method is that it requires the geometry for the particular specimen to be known *a priori*. There are other techniques for crack opening stress measurement such as high resolution optical microscope [8], interferometry and through heat generation in vibrating cracks [9], but they are not suitable for real-time applications.

Recently it has been found that the echo pulse amplitude in ultrasonic detection of cracks is affected by crack closure due to the presence of compressive stress across the crack faces. Thavasimuthu [10] conducted experiments on simulated cracks at the root region of a butt-weld joint to show ultrasonic response of crack closure due to residual compressive stress. Several other researchers have used surface acoustic waves to describe crack opening stress phenomenon [11] and showed that the surface wave signature is dependent on fatigue load and crack tip opening stress. Mi et. al. [12] have shown that ultrasonic is quite sensitive to microstructural changes of materials and can be used for dynamic monitoring of fatigue crack initiation and growth. The energy ratio is used for detection and estimation of fatigue damage, which is defined as the ratio of energy of transmitted ultrasonic signals at anomalous condition and nominal condition. Gupta et. al. [13][14] have used time series data of ultrasonic sensors for anomaly detection in the statistical behavior of structural materials, where the analysis is based on the principles of symbolic dynamics and automata theory [15].

This paper shows that ultrasonic response of crack opening and closing cycle under fatigue load, is sensitive to distinguish the crack opening stress during one load cycle. The energy of reflected ultrasonic signal is used for the measurement of crack tip opening stress. The experimental results are presented and compared with the Newman's model [3] for finding crack opening load. It is also proposed that the real-time crack opening load measurement can be used for quantifying damage and damage increment for life-extending control of mechanical structures [16].

This paper is organized into four sections including the current section which introduces the importance and need for online measurement of crack opening load. Section II describes the experimental apparatus, details of the test specimen, and test procedure for measurement of crack tip opening load. Section III presents the experimental results for validation of the crack opening stress model. The paper is concluded in Section IV along with recommendations for future work in this area.

II. Experimental Apparatus and Test Procedure

This section presents the details of experimental apparatus for measurement of crack opening load based on ultrasonic sensors. It also describes the details of the test specimen and the test procedure.

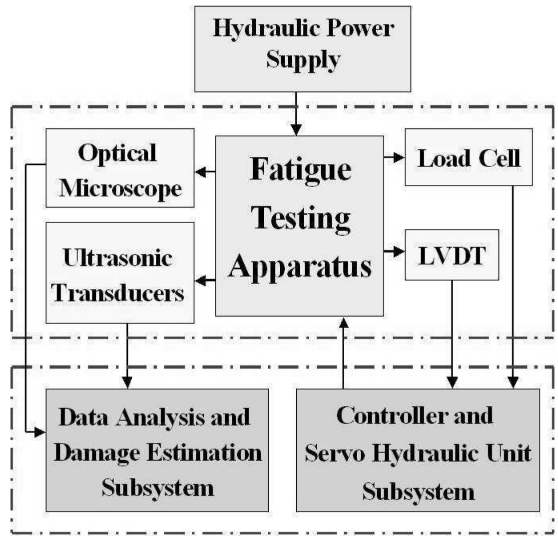

Fig. 1. Schematic of the fatigue test apparatus system

A. Description of the Experimental Apparatus

This subsection describes the experimental apparatus that is designed to study the fatigue damage growth in mechanical structures. The primary objective of the fatigue test apparatus is to demonstrate online sensing and prediction of fatigue damage. As such, the requirements of the apparatus are:

- Capability to operate under cyclic loading with multiple sources of input excitation;
- Provision of a failure site such that the damage accumulation takes place within a reasonable period of time in the laboratory environment with negligible damage to other components of the test apparatus;
- Capability of real-time data acquisition from appropriate sensing devices
- Accommodation of online data analysis tools for monitoring the evolution of fatigue damage in real time.

The experimental apparatus operates on the power delivered by an electric-motor-driven hydraulic pump system. Figure 1 presents the schematic of the test bed consisting of the fatigue damage testing apparatus and the auxiliary equipment. The fatigue damage test apparatus contains MTS 831.10 Elastomer Test System as shown in Figure 2. The Elastomer system has static ratings of ±15kN in force and ±50mm in displacements and under dynamic loading it can go as high as 200Hz at lower amplitudes. This is integrated with Olympus BX Series microscope with a long working-distance objective. A camera mounted on the microscope takes images which have a resolution of 2 micron per pixel at a distance of 20mm. An ultrasonic board is used to send pulses to the transducer to generate ultrasonic wave and receive the reflected signal. Various components of the test apparatus exchange information from sensors, microscope, and fatigue test as data packets over a TCP/IP network in real time. This information can be used for online anomaly detection and health monitoring. The apparatus is equipped with the following two additional sensing devices that are used by controller.

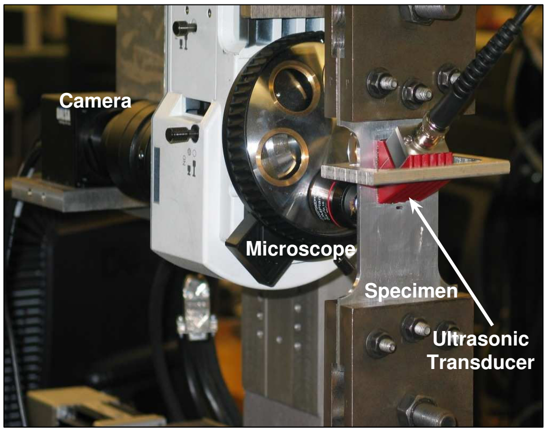

Fig. 2. Pictorial view of the fatigue test apparatus

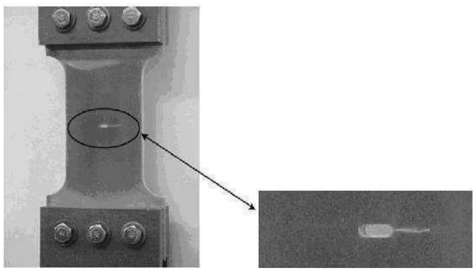

Fig. 3. Center notch specimen with crack

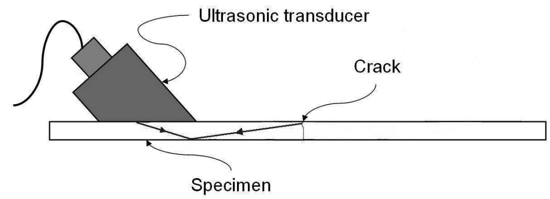

Fig. 4. Ultrasonic transducer fitted on a specimen

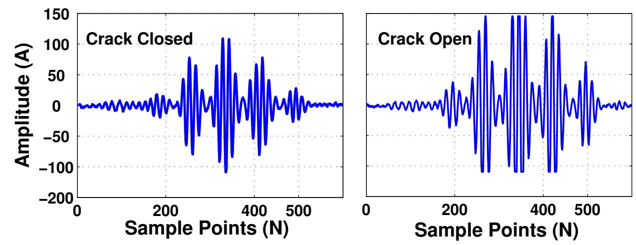

Fig. 5. Ultrasonic response to closed crack and open crack

1) An Extensometer (LVDT) for position measurements;
2) A Load cell for load measurements.

B. Specimen Details

The specimens used in the experiment are made of 7075-T6 aluminium alloy having a flat plate shape as shown in the Figure 3. A center notch is provided in the specimen to act as a stress riser which helps crack to be initiated at its end. The specimen is 3 mm thick and 50 mm wide, and has a slot of 1.58 mm×4.5 mm at the center. This specimen is designed to fail in a relatively short period of time under a specified load range so that the characteristics from crack initiation to fracture can be analyzed with the help of ultrasonics and microscope. The specimen is subjected to tensile-tensile fatigue loading during the experiment. The details of experimental procedure is described in the section II-C.

C. Test Procedure

The 7075-T6 aluminum specimen (see Section II-B) with a center notch and initial crack of length ~ 5 mm is tested on the fatigue test apparatus. A piezoelectric standard angle beam transducer is firmly attached to the specimen at such a location that the ultrasonic wave passes through crack tip region as shown in Figure 4. The element size of the transducer is ~ 13 mm, which is larger than the crack length to cover whole of the crack. Angle beam transducers are single-element transducers used with a wedge to introduce a refracted shear wave or longitudinal wave into a test piece. Electrical pulses are sent to the ultrasonic transducer at periodic intervals to enable the transducer to inject ultrasonic waves of 3.5 MHz frequency in the specimen. A fraction of ultrasonic wave is reflected from the cracked surface, which is received by the same transducer. The amount of reflection is dependent on the crack length and the contact area between two crack surfaces. Any other discontinuities in the specimen (e.g., voids, dislocations and small interior cracks) may cause change in the signature of signal received by the transducer. The received ultrasonic signal is transmitted to the data acquisition system that stores data in memory chip.

Measurement of the crack opening load requires application of a cyclic load on the specimen at a very low frequency (e.g., 0.01 Hz). The load cell is synchronized with the ultrasonic pulsar which gives the measured load value at the instants of ultrasonic pulses. The relevant data (i.e., received ultrasonic signal and corresponding load) are stored in a computer which is used for analysis of crack characteristics. In parallel, the optical microscope is used to observe crack characteristics and images of the crack tip are taken at an interval of 5 Seconds. Two sets of experiments are conducted, the first with load varying from 0 to 6000 N and the second with load varying from 0 to 4000 N. For each set of experiment, the machine is run for about 25 minutes to collect sufficient amount of data for analysis. The experimental results are analyzed in the next section.

III. Analysis of Test Results and Validation

This section analyzes the experimental results for model validation of crack tip opening stress in 7075-T6 Aluminium alloys. A sinusoidal load with constant amplitude varying from 0 N to 6000 N and frequency 0.01 Hz is applied on a center-notched cracked specimen with initial crack length of ~ 5 mm and ultrasonic data is acquired as described in Section II-C. To characterize the crack closure process, the energy of received ultrasonic signal is calculated as

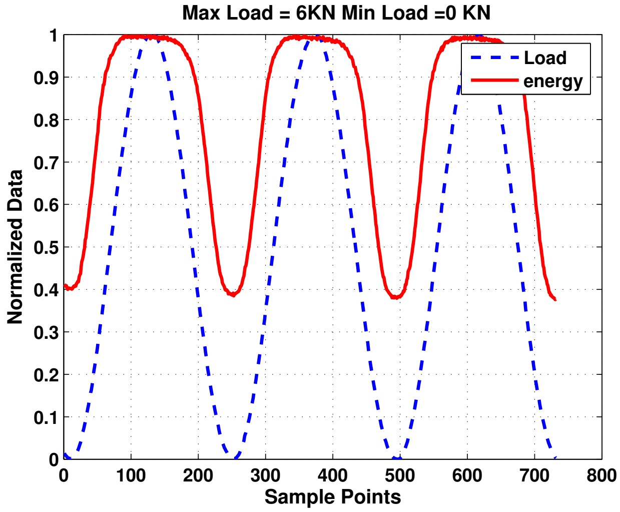

Fig. 6. Normalized Load and energy of ultrasonic signal (S_{max} = 6 kN)

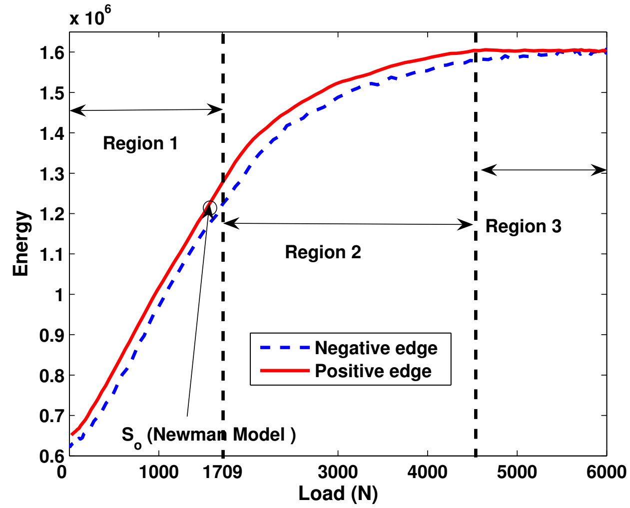

Fig. 7. Load versus energy of ultrasonic signal (S_{max} = 6 kN)

$$E_t = \sum_{k=1}^{n} (A_k)^2 \quad (4)$$

where n is total number of sampling points during one ultrasonic pulse (in the tests, $n = 600$); and A_k is amplitude of ultrasonic wave for k_th sampling point. Figure 5 shows ultrasonic signal received when crack is fully closed and fully open. The amplitude of received signal is higher when crack is open as larger fraction of ultrasonic wave is reflected from the crack surface, while a small fraction is reflected when crack is closed.

The noise in the computed energy of ultrasonic data is filtered by a fourth order FIR filter and then normalized. Figure 6 plots the normalized ultrasonic energy and the corresponding normalized applied load for three load cycles. It is seen that, at the minimum load, the energy of the reflected signal received by the transducer is also minimum and increases with the applied load on the specimen. This is due to opening of the portion of the crack near the center notch, thereby causing an increase in the reflection of the ultrasonic energy. The energy of the reflected signal saturates near the maximum load when the crack is fully open and later on starts decreasing at the onset of crack closing as seen in Figure 6.

To understand the crack opening phenomenon, ultrasonic energy is plotted against load for one complete load cycle as seen in Figure 7, where the loading part of the stress cycle is plotted by solid line and the unloading part is shown by dashed lines. The nature of this curve is similar to the ultrasonic energy curve in Figure 6, which is first linear, then nonlinear, and finally becoming flat indicating the region where crack remains fully open.

The ultrasonic energy curve is divided into three regions as shown in Figure 7. The first region spans from zero load to the onset of crack tip (defined as the region ∼0.1 mm from the tip) opening, where the ultrasonic energy increases (approximately linearly) with a constant slope. As described earlier, in this region the portion of the crack near the center notch opens; thereby causing an increase in the reflection of the ultrasonic energy. However, the crack tip is still closed, thus no crack propagation takes place. In second region, the ultrasonic energy curve becomes nonlinear and the crack tip gradually opens. In third region, the ultrasonic energy becomes almost flat and shows no change with the increasing load, which indicates that the crack and the crack tip are fully open in this region and there is no change in the contact area between crack surfaces with the increasing load. The following paragraph reiterate these observations to explain the crack growth process in terms of the crack closure phenomenon.

Figures 6 and 7 describe the crack closure phenomenon for the 7075-T6 aluminium. The first region where ultrasonic energy increases linearly with increasing load represents the duration when the crack tip portion (defined as the region ∼0.1 mm from the tip) remains closed and hence does not propagate. In this region since S_{max} lies in this range, there is no increase in the crack length; so, it does not contribute to ΔK^{eff}. In the second region where ultrasonic energy increases nonlinearly with the increasing load represents the duration when the crack tip is opening. Therefore, the load at which the curve becomes nonlinear is defined as the crack tip opening stress (S_o) and used for the calculation of ΔK^{eff} in Eqn. (1). At this stage, the plastic zone around crack tip is depleting, which contributes to crack propagation because $S_{max} > S_o$ and $\Delta K^{eff} > 0$. Once the crack tip is fully open, there is no contact between the two crack surfaces. Hence, there is no further change in the ultrasonic energy with increase in the applied load. A major part of crack propagation occurs in this region. The ultrasonic energy curve during unloading is similar with a small ultrasonic energy hysteresis visible in Figure 7; it is observed that the crack closing stress is slightly less than the crack opening stress for this material and under this loading condition.

It is important to distinguish region 1 from region 2 in

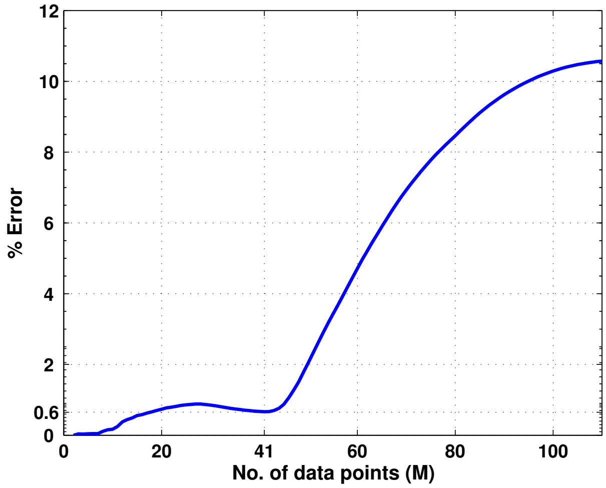

Fig. 8. % Error versus total number of data points

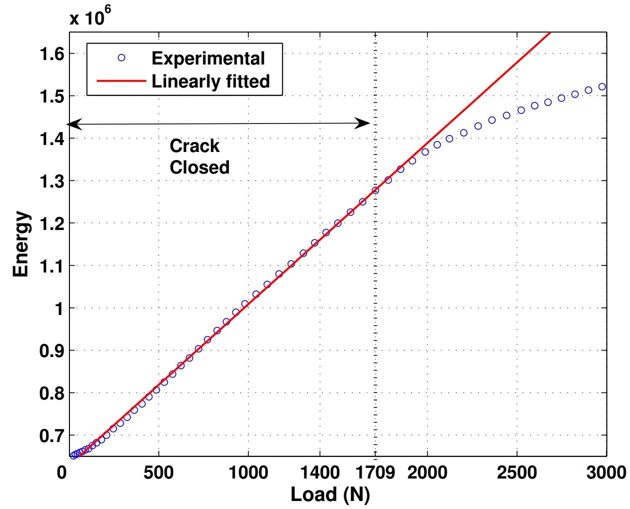

Fig. 9. Experimental and linearly fitted curves of ultrasonic energy

Figure 7, where the curve changes its behavior from linear to nonlinear. To identify region 1, a straight line is fitted to first few data points of load-ultrasonic energy curve using the least square method. Percentage error is defined as:

$$\%\text{Error} = \frac{||E_{\text{fit}} - E_{\text{exp}}||_2}{||E_{\text{exp}}||_2} \times 100 \tag{5}$$

where $|| \bullet ||_2$ is the standard Euclidean norm; E_{fit} and E_{exp} are the vectors containing energy values obtained from the linear fit and experimental observation for first M data points respectively. This procedure of fitting a straight line and calculating percentage error is repeated by augmenting E_{exp} with the next data point. The objective here is to find the largest set of data points E_{exp} which follow a linear relationship with load. This is achieved by choosing the set of data points that minimize the error. Figure 8 plots the error as a function of number of initial data points used to fit a straight line. The plot shows that, for first 41 data points, the error has a local minimum, which is considered to be the best data set for linear portion of the load-ultrasonic energy curve. This data set of first 41 points is fitted with a straight line; it is plotted along with the actual load-ultrasonic energy curve in Figure 9. The load, where the fitted line starts deviating from the experimental curve, is considered as the crack opening load. Figure 9 plots load only till 3000 N to magnify the region where the experimental curve deviates from the fitted straight line. It is concluded from Figure 9 that, at about 1709 N, the curve becomes nonlinear and is denoted as crack opening load for the corresponding load cycle. It is also comprehended that the crack tip becomes fully open at 4500 N load; hence, the ultrasonic energy saturates and its plot with load becomes flat. The constitutive relation of Newman [3] described by Eqns. (2) and (3) yields 1500 N as crack opening load in contrast to the experimental observation of 1709 N. This relatively small discrepancy is attributed to the stochastic behavior of the material, measurement errors, and empirical nature of the constitutive equations. Specifically, a potential source of inaccuracy is the constraint factor α that varies from 1 (plane stress) to 3 (plane strain) [3].

To validate the constitutive relation of Newman [3] with experimental observation, one more experiment is conducted on the same cracked specimen with a maximum load of 4000 N and a minimum load of 0 N. The frequency of load cycles was 0.01 Hz and the profile of load cycles was triangular as shown in Figure 10. The energy curve is not expected to have any flat region because the maximum load is below the yield point at 4500 N. Figure 10 validates this fact as there is no saturation of ultrasonic energy in this case. Figure 10 plots normalized load and ultrasonic energy as a function of time under the described loading. The ultrasonic energy curve is linear first and then it becomes non linear before reaching to peak. It never becomes flat which indicates that crack tip is not fully open during the whole loading cycle. The ultrasonic

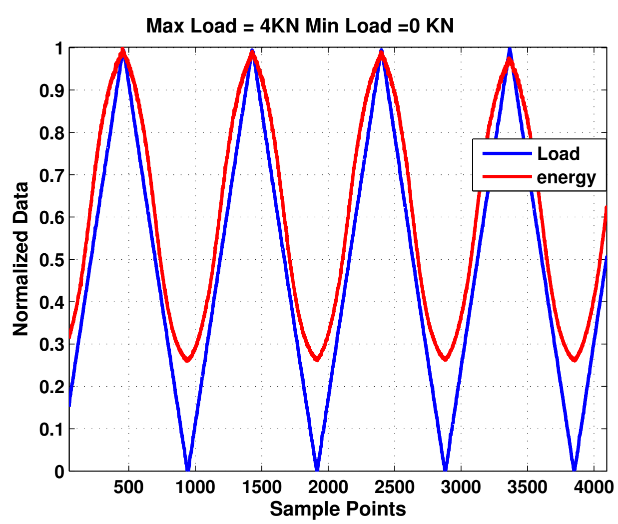

Fig. 10. Normalized load and energy of ultrasonic signal (S_{max}= 4 kN)

energy curve becomes slightly nonlinear near the peak load. This indicates that the crack tip is just opening and begins to contribute to the effective stress intensity factor.

IV. Conclusions and Future Work

This paper addresses usage of ultrasonic sensors for real-time measurement of crack opening stress in cyclically loaded mechanical structures. The objective is to compute fatigue damage and damage rate by ultrasonic sensing that is fast and accurate for online measurement of crack opening load. The experimental results on a fatigue test apparatus agree with the results obtained from well-established constitutive relations for computation of crack opening stress. The work reported in this paper suggests that measurements of crack opening stress by ultrasonic sensing and associated signal conditioning could be available for real-time health monitoring and life extending control. The following future work is suggested by authors in order to use crack opening information in real-time life extending control of mechanical systems.

- Investigation of the effects of different types of fatigue loading i.e., underload, overload, step loading and block loading on crack opening stress;
- Formulation and experimental validation of fatigue damage models for variable-amplitude cyclic loading;
- *Analysis and synthesis of a life-extending control system*: The crack opening stress is an important parameter in estimating the current damage rate and remaining life of a mechanical component under fatigue loading. Real-time measurement of crack opening stress using the proposed method can be fitted to appropriate damage model to obtain a measure of total damage and instantaneous damage rate. These two variables can be used as feedback parameter for a gain-scheduling control system. The purpose of gain scheduling is to adapt to the plant health condition for extension of its service life and enhanced safety and reliability[17]. A gain scheduling controller may make use of a set of linear controllers, where the controller in action is determined based on the gain scheduling variables.

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