# Fatigue Crack Closure Analysis Using Nonlinear Ultrasound

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## Abstract

In order to analyze the crack closure of a fatigue crack, nonlinear ultrasound is applied. In introduction of fatigue crack we develop the crack opening monitoring procedures using TOFD method to obtain the reliable result about the relation between crack opening displacement and nonlinear ultrasound. Longitudinal ultrasonic wave of 6.4MHz in frequency with large amplitude incident to the three point bending aluminum alloy and SUS316 stainless steel specimen. Angle probe transducer fabricated in this experiment was used for a measurement of nonlinear ultrasound. As the results, remarkable subharmonics of 3.2 MHz in frequency was observed in both materials specimen of aluminum alloy and SUS316 stainless steel. However secondary superharmonics of 12.8 MHz was observed only in aluminum alloy specimen and detail of the behavior for each material was different. Mechanism of subharmonics was also investigated.

Key words: SUS316, nonlinear ultrasound, fatigue crack, closure, simulation

## 1. Introduction

Nonlinear ultrasound has been extensively used in evaluation of solid lattice defects, and in medical ultrasonic diagnosis. In recent years, nonlinear ultrasound was found to be useful for detection and estimation of cracks, especially for closed cracks which were difficult to detect using conventional linear ultrasonic measurement methods. When ultrasonic wave with a large amplitude incident to a crack, nonlinear component of superharmonic [1] and subharmonic [2, 3] waves are generated at the crack. Amplitude of each harmonic wave is reported to depend on a crack opening displacement. Superharmonics is easily generated, not only at an imperfect interface such as a closed crack but also in a coupling medium and in a wedge for an angle probe. On the contrary, the subharmonics is suitable for evaluation of a closed crack because it is generated only at imperfect interfaces.

In the analysis of the mechanism of subharmonics, several analytical investigations were applied and the similarity with a contact problem in atomic force microscope [4] was also pointed out [3]. However previous experimental data did not pay enough attention to crack opening displacement though the crack closure are supposed to strongly affect the nonlinear behavior. Furthermore, since the geometric shape of cracks investigated in previous studies [2,3] is complicated, quantitative comparison between experiment and analysis was not attempted.

In introduction of a well-defined closed fatigue crack, thus, authors have made a crack which cannot be detected by linear ultrasound without applying a bending load, monitoring the amplitude of a crack tip echo by the ultrasonic pitch catch method [5]. Consequently, in nonlinear measurement, quantitative control of a crack opening was reversibly realized by applying slight load to the closed fatigue crack. Using these procedures, behaviors of superharmonic and subharmonics were observed [6] and analyzed [7,8]. Until now, aluminum alloy A7075 has been used for the following reasons; ultrasonic attenuation is small realizing high S/N measurement, crack surfaces do not rust during measurement, and mechanical property data needed for controlling the stable fatigue crack growth are available.

In this study, nonlinear measurement is performed using stainless steel SUS316L in addition to the aluminum alloy A7075 and compared their results. Obtained waveforms containing superharmonics and subharmonics are analyzed using wavelet analysis method. Furthermore, based on the behavior of the subharmonic wave obtained in these experiments, the Lennard-Jones type nonlinear contact model [7,8] is investigated, and the cause of generation of subharmonic wave is discussed.

## 2. Experiment Method

In introduction of a closed fatigue crack at no-load, fatigue testing conditions were precisely controlled by the stress intensity factor $K$ using three point bending fatigue specimen. During the crack propagation, $K$ at the crack tip was kept constant and crack opening was monitored by measuring the amplitude of crack tip echo with the ultrasonic pitch catch method. Longitudinal angle probes of 5MHz were applied for the monitoring. In tensile fatigue condition of bending, the combinations of the maximum and minimum stress intensity factor were changed and the adequate conditions of a closed crack were investigated for each material.

Experimental setup for nonlinear ultrasound measurement is shown in Fig.1.

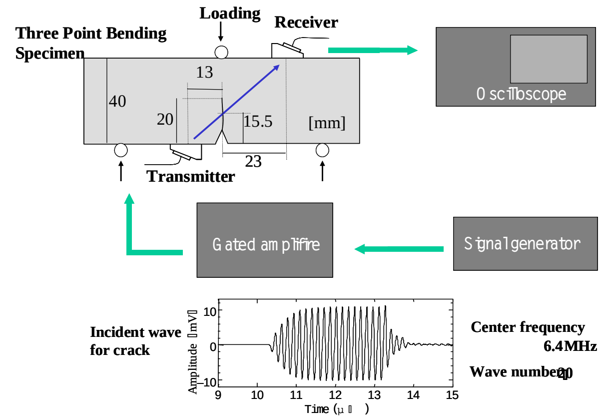



Fig.1 Nonlinear ultrasound measurement setup

Combining the signal generator and the gated amplifier, ultrasonic tone burst of 20 waves was generated. For the nonlinear measurement a large displacement over 10nm is required at a crack surface. In order to tolerate the high voltage excitation, the 45-degree angle probe for transmission was fabricated as a prototype using a 6.4MHz longitudinal piezoelectric device. The probe for receiver was a commercial wide band longitudinal probe of 5 MHz or 10 MHz in center frequency. At the nonlinear measurement, the crack opening can be controlled by static bending load and the amplitude of incident ultrasound can be also changed.

## 3. Experimental result

For an aluminum alloy A7075, the transmitted

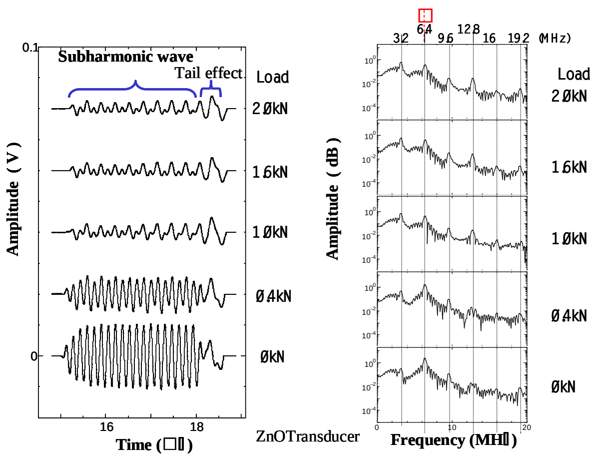



Fig.2 Waveforms due to applied load (Aluminum alloy A7075)

waveforms through a crack by angle beam measurements are shown in Fig. 2.

Frequency analysis using FFT for transmission echo is also shown in this figure. As the applied load was changed from 0 to 2kN, waveform and spectrum were changed due to the generation of harmonic waves. The maximum load of 2 kN was decided as 90% of maximum applied load peak in the fatigue propagation test. In waveform, the amplitude of transmission wave decreased due to the crack opening by loading and at the same time characteristic disorder can be increased in the whole received waveform. These disorders relate to the generation of nonlinear components which appeared as the many frequency peaks as shown in the FFT results.

Especially the amplitude change of the peak of 3.2MHz subharmonic wave showed a remarkable increase due to the applied load. The amplitude ratios of second harmonics and subharmonics to the fundamental wave against the applied load are shown in Fig. 3. Each ratio increased with the load and after showing a peak it slightly decreased. Although other peaks of amplitude were small the same tendency was observed.

In order to examine the material dependence, stainless steel SUS316L which has a large problem of SCC (Stress Corrosion Crack) in the structures of nuclear electric power generation was used in addition to the aluminum alloy A7075. Shape of the specimen, measurement procedures and so on was all same as the one of A7075. The received wave waveform and its frequency-analysis result by FFT by 45 degree angle beam measurement were shown in Fig. 4.

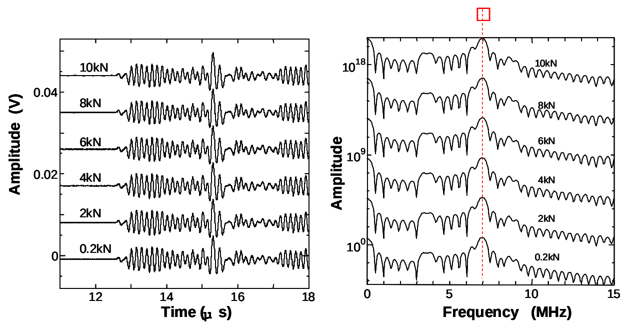



Fig.4 Waveforms due to applied load (Stainless steel SUS316L)

For the applied load of from 0.2 to 10kN, waveform and spectrum were observed. Although the maximum load of 10kN was decided as same 90% of maximum applied load in the fatigue test as A7075 specimen, differences due to applied load were quite small both in waveform and spectrum. However a disorder after the middle position of waveform was similarly observed for all the loading conditions which might be identified as the subharmonics.

Furthermore, the amplitude of incident ultrasonic wave was changed by using the gated amplifier and the waveform and the spectrum were observed. Results were shown in Fig.5.

Due to the amplifier gain index (GA) from 6.0 to 7.7, amplitude of incident ultrasonic wave was increased.

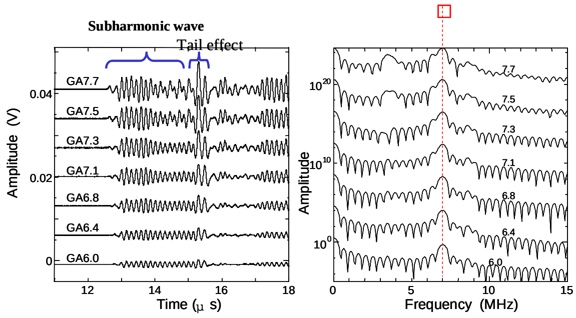
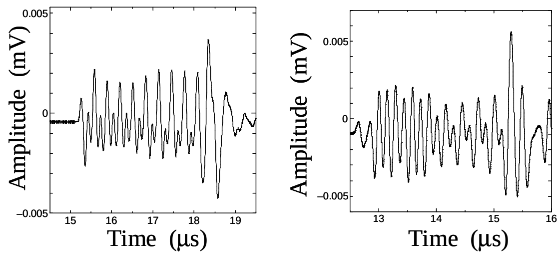



Fig.5 Waveforms due to incident wave amplitude (Stainless steel SUS316L)

When the input wave amplitude was small with the GA less than 6.4, a received waveform was close to the sine burst wave which was an input waveform and nonlinearity was not seen. When the amplitude was increased above GA of 6.5, the amplitude in the latter part of received waveform began to decrease. Moreover at GA of 7.5 or more, a disorder generated by subharmonics can be observed in the latter part of received waveform. The tail effect [8] also appeared clearly.

As to the superharmonics, any superharmonics were not observed in SUS316L, though many superharmonics were observed in aluminum alloy A7075.

Although, as shown above, a nonlinear behavior could also be observed in SUS316L, the details were different from that in A7075. To clear and quantify the difference of the waveform behavior of both materials, wavelet analysis was applied. The sample of the waveforms and the results were shown in Figs 6 and 7, respectively.

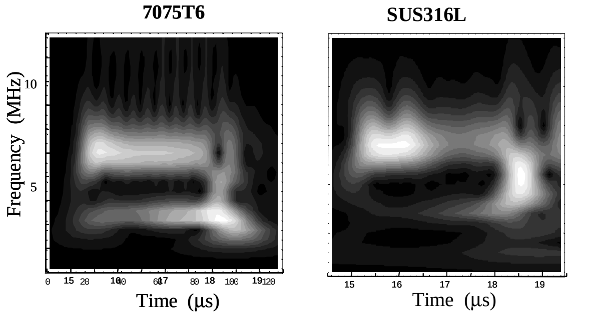



7075 Aluminum Alloy
Applied Load 2.0kN

Stainless Steel SUS316L
Applied Load 10kN

Fig.6 Typical waveform of each material

These patterns indicate the time dependence of the spectrum from the initial point to the tail part of the each waveform.




7075 Aluminum Alloy
Applied Load 2.0kN

Stainless Steel SUS316L
Applied Load 10kN

Fig. 7 Wavelet analysis of each material

The difference of the wavelet pattern might be used to quantify nonlinear ultrasound behavior which directly relate to the evaluation of the characteristic of the crack.

Although the cause of these difference due to materials is not clear, these are supposed to relate to the three dimensional shape of the crack, and to the difference in the elastic properties. Conversely, the nonlinear measurement will have the potential to reveal the crack shape and material properties.

## 4. Discussions

In order to investigate the cause of generating a subharmonic wave, we proposed the following model [7,8].

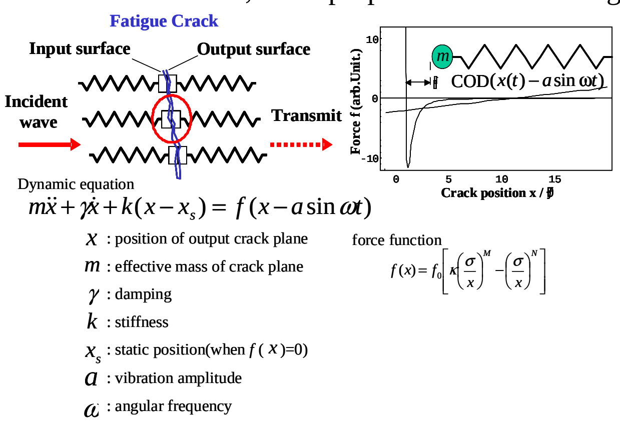



Fig. 8 Contact crack model for subharmonic wave

In this model as shown in Fig.8, large displacement ultrasonic wave is traveling from the left side and excite a forced oscillation of the left side of crack plane and the oscillation is transmitted by contact to the crack plane B. When an ultrasonic wave with the large displacement $a$ incident from the left of the crack, and the average crack opening $x_S$ is larger than $a$, both crack planes will not contact

each other and will not transmit an ultrasonic wave. If $a$ exceeds $x_S$ , contact will take place, an ultrasonic wave will be transmitted, and a right crack plane will also vibrate according to the vibration of left crack plane. Furthermore, if the incident ultrasonic wave displacement is large, the output crack plane is vibrated differently from the input crack plane. This action might cause the subharmonics in transmitted wave through a crack.
When crack plane A is vibrated with an amplitude $a$ and an angular frequency $\omega$, the displacement of crack plane B follows [7]

$$m\ddot{x}+\gamma\dot{x}+k(x-x_S)=f_0\left[\kappa\left(\frac{\sigma}{x-a\sin\omega t}\right)^{M}-\left(\frac{\sigma}{x-a\sin\omega t}\right)^{N}\right] \quad (1)$$

where, $x(t)$ is the position of crack plane B, $f_0$ is the magnitude of force, M is the repulsive force index, N is the attractive force index, $\kappa$ is the ratio of attractive to repulsive force, and $\sigma$ is a characteristic length for crack planes. These dynamic equations express the balance of the inertia, the elastic stiffness in contact, and the compliance of a crack shown as the power function. Although repulsive force and attraction forces in a power function includes unknown indices M and N, the geometric shape and the elastic characteristic of the crack can be modeled using these indices [7].

As an example of the simulation, the transmission waveform through the crack in the case of the input ultrasonic wave displacement with average crack opening of $5.2\sigma$ to $11.3\sigma$ is shown in Fig.9 [8].

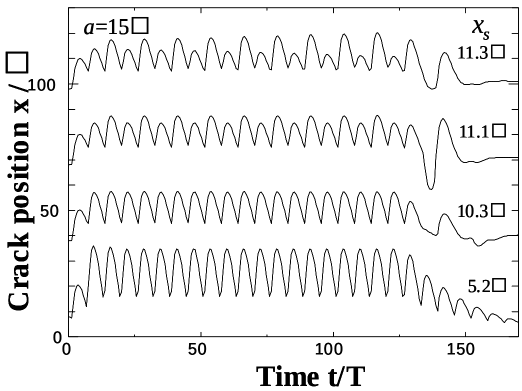



Fig.9 example of the simulation

As a corresponding example of experimental waveform of a crack length of 9.8 mm, and applied load of 0.06 kN to 1.6 kN in aluminum alloy is shown in Fig.8. Comparing Figs. 7 with 8, both agree well and subharmonic wave can be simulated qualitatively. For the tail effect [8], simulated wave agree well to the experimental results. After the several simulations changing the initial conditions of $a$ and $x_S$ , the subharmonic behavior appears notably in the limited conditions. Although the formulation of this simulation [7,8] has a point which should be carefully examined, it seemed to be effective for the qualitative or semi-quantitative estimation for subharmonic behavior.

As to the superharmonics, any superharmonics could not be observed only in SUS316L. This could be supposed to relate the large acoustic attenuation of SUS316L due to the microstructure. In power generate structure, fatigue cracks or SCC are introduced in weld part which shows lager attenuation than base metal. Thus, low frequency subharmonics supposed to be superior to high frequency superharmonics for the measurement of high attenuated materials.

Nevertheless, to obtain the more accurate estimation for the subharmonic phenomena, additional experimental data and the more detailed information of crack will be required.

## 5. Conclusion

In order to examine the material dependence on subharmonic wave, stainless steel SUS316L was used in addition to the aluminum alloy A7075. Nonlinear behavior could also be observed in SUS316L, although the details were different from A7075. To investigate the subharmonic behavior in a fatigue crack, wavelet analysis and proposed contact model and its simulation was applied. The simulation agrees well to the experimental data qualitatively.

## 6. Acknowledgement

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