

# Study of Anti-Symmetric Flexural Mode Propagation along Wedge Tip with a Crack

Manikanta Prasad Banda, Che Hua Yang

**Abstract**—Anti-symmetric wave propagation along the particle motion of the wedge waves is known as anti-symmetric flexural (ASF) modes which travel along the wedge tips of the mid-plane apex with a small truncation. This paper investigates the characteristics of the ASF modes propagation with the wedge tip crack. The simulation and experimental results obtained by a three-dimensional (3-D) finite element model explained the contact acoustic non-linear (CAN) behavior in explicit dynamics in ABAQUS and the ultrasonic non-destructive testing (NDT) method is used for defect detection. The effect of various parameters on its high and low-level conversion modes are known for complex reflections and transmissions involved with direct reflections and transmissions. The results are used to predict the location of crack through complex transmission and reflection coefficients.

**Keywords**—ASF mode, crack detection, finite elements method, laser ultrasound technique, wedge waves.

## I. INTRODUCTION

THE stainless steels are used in turbine engine blades due to their excellent machinability, strength, high melting point, and corrosion resistance. However, a series of new technical problems have arisen under high-pressure conditions due to surface cracks. It affects the performance and reliability of the structural components and decreases the service life. Therefore, the application of defect identification techniques is necessary to improve the service life of stainless-steel blades with higher performance. To reach defect detection, there are many techniques such as tip timing, vibrational monitoring, temperature measurements, and nondestructive methods (NDT) are used in defect detection. The most widely used NDT detection technology is the Laser Ultrasound Technique (LUT). In this method, the laser generates elastic waves on the surface as guided waves, these waves are wedge waves (WW) known as ASF modes propagating along the edge surface with less wave velocity, long propagation, and high amplitude observed in the time-domain signal.

In the early 1970's, the well-known researchers Lagasse et al. discovered the WW by performing mathematical study [1], [2], which has exceptional properties such as transmitting ability along the tip of wedge, strong localization, dissimilar scattering characteristics, truncated wave rate. In recent years, a lot of researchers proved that the WW can be exploited in

engineering strategies and other technical and non-technical applications; such as the estimation of theory in a thin plate proved that the plate theory [3]. The geometric theory in NDT techniques [4] is only effective for small-angled wedges. The finite element approach (FEM) was used to consider the propagation of WW properties. From the experimental data, it was noticed that the angle of the wedge has control over the velocity of the acoustic waves [5]. When waveguide operated at different thicknesses, the stress and displacement fields were obtained by mathematical simulations at different slope angles and frequencies [6]. Jia and De Billy [7] first utilize the property of the WW and examine the association among mode number and angle, and they investigated the effects of apex truncation and curvature radius on the dispersion property. They describe how phase velocity spreads with curvature and compare their primary findings with the Krylov [8], which examined a small-scale mono hull model using a localized flexural wave that spreads along a plate of finite width creating a vessel capsized [9]. Yang and his co-worker [10] examined the circular matrix with LUT, of bilinear cross-sections and their effect [11] and wave propagation of antisymmetric mode along the apex of piezoelectric wedges, [12] wedge tips with notch defect [13]. However, crack detection in micro and macro size become complicated in complex structures. The LUT experimental results and numerical finite element analysis simulation of wedge waveguide are suitable for the observation of the wave propagation phenomena. In the signal processing part, most of the transmission and reflection coefficients are estimated using the maximum amplitude of the time domain signal, but in fact, during the transmission of the time domain signal, the wavelength and amplitude will change due to the frequency domain change, which could be affect the use of the maximum amplitude. The RAM-5000 SNAP is the important component of the nonlinear measurement method in the principle of amplitude and ultrasonic subharmonics in nonlinear defect detection explained by subharmonic resonance and cracks localization affects nonlinearity in response signals.

## II. METHODOLOGY

### A. Specimen Preparation

The specimen selected for this experiment is 304 Stainless Steel (SS) with an angle of 60° edge base test material. Initially, a rectangular notch is created by using a rotary cutting machine. Then, with the help of the material testing system (MTS) and computer aided improved wire cutting machine (EDM) partially contacted surface crack along with edge tips of different lengths of cracks is created.

Manikanta Prasad Banda is a Ph.D. student at National Taipei University of Technology, Taipei city 106, Taiwan (phone: 02-27712171 extn 4817; e-mail: manikantabanda9@gmail.com).

Che Hua Yang is a professor in the department of Graduate Institute of Manufacturing Technology at National Taipei University of Technology, Taipei city 106, Taiwan (phone: 02-27712171 extn 4814 e-mail: chyang@ntut.edu.tw).

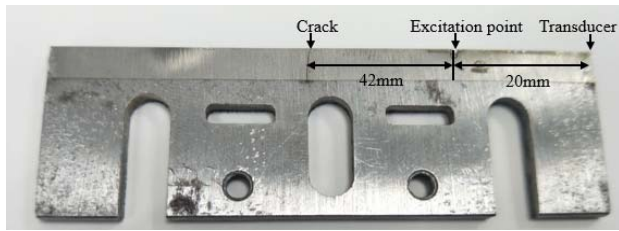


Fig. 1 An elastic stainless-steel specimen with wedge crack

The dimensions of the specimen are length 153 mm, height 30 mm and thickness 3 mm as shown in Fig. 1 and a schematic diagram of the test piece designed in numerical analysis software is shown Fig. 2 in order to represent the experimental test specimen.

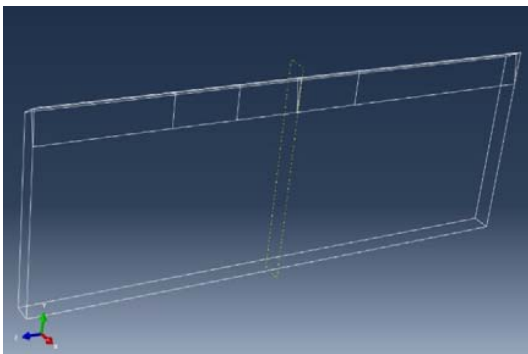


Fig. 2 Schematic figure of the test piece designed in FEM

### B. Tensile Test

A fretting test fixture was designed and developed which was coupled with a servo-hydraulic subjected to a constant

amplitude fatigue loading of MTS machine, with a maximum load of 100 kN with point load, as shown in Fig. 3 to simulate force and forms of kineticism of the materials, structures, and product of the fretting fatigue damage.

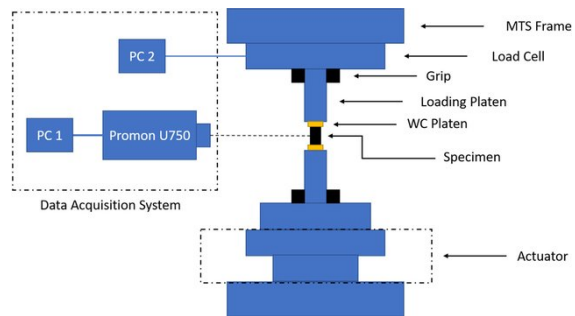


Fig. 3 Schematic view of tensile load testing setup

The specimen was clamped by the tensile vertical pretends and fixtures under pressure with the same force for every test to minimize operator errors and adjustable pressure sanctions pretend to test materials. Initially, a notch was created on the wedge to get perfect crack. The tensile point load along the y-axis is applied gradually in order to maintain a constant speed for the machine. In order to get a perfect crack gradually applying pressure load on the specimen from 0 kN to 90 kN. crack zone is formed at the force of 38 kN and 1.3 mm from original displacement in the fretting test cycle as shown in Fig. 4. After the test, top notch is removed by cutting tool, then a perfect and clear crack is obtained.

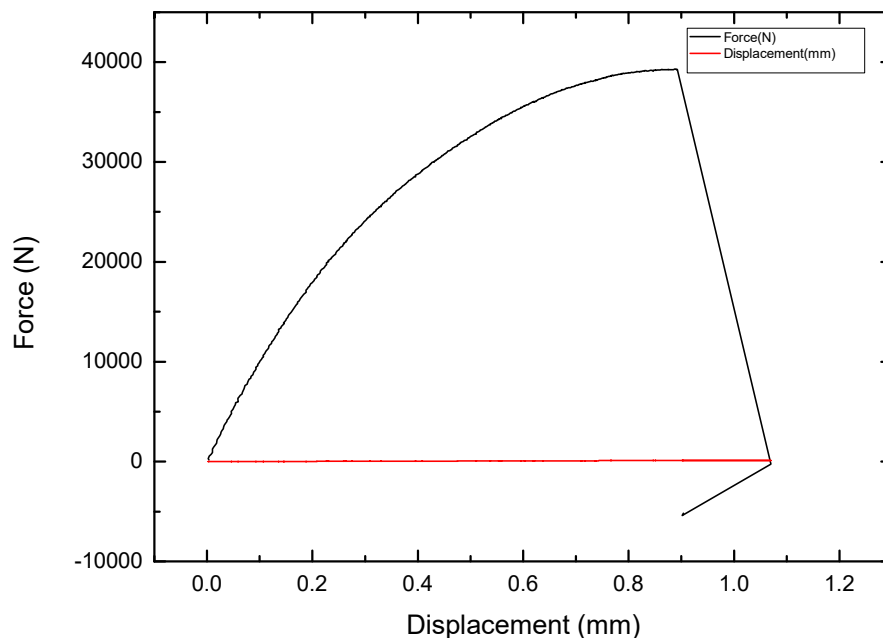


Fig. 4 Fatigue test cycle under load vs displacement

### C. Laser Ultrasound Experiment

Laser ultrasonic quantification technique is used to detect the electrical dispersion of the time domain signal and the antisymmetric mode waveguide is distributed on the body plane blade. In the present study, pulsed Nd: YAG laser is used at a wavelength of 532 nm and a pulse duration of 6.6 ns to produce an ultrasound beam with a Gaussian energy distribution that occurs on the surface of the test piece with wrinkles. The piezoelectric shear transducer is used to receive the A-scan signal from the test specimen. The time domain signal of the excitation and receiver positions can clearly distinguish between the incident and reflected wave signal, and receiving the excitation laser of the present experiment shown in Fig. 5 of the complete setup of the experiment.

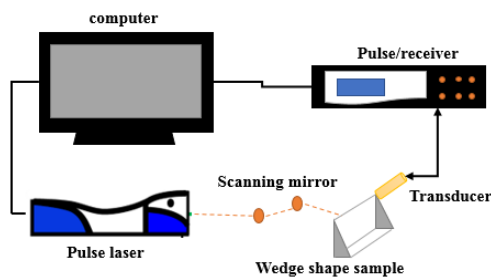


Fig. 5 Laser Configuration

### D. Finite Element Simulation

The FEM analysis software (ABAQUS) must be defined on the appearance characteristics of the test sample analysis model and the material properties set, the boundary conditions set, the preparation of the mesh node and the prework processing, and so on, and finally the simulation analysis and the result are obtained. A SEAM describes the edge or face of a model that is initially closed but can be opened during an analysis. When the mesh is created, Abaqus/CAE places overlapping duplicate nodes along the seam. The seam cannot stretch along the boundary of a part and must be inserted within the face of a two-dimensional part or within the cell of a solid part. Once a seam is formed, we evaluate its crack properties by means of an integral contour analysis. Crack elements on both sides of the partition will be connected to each other: they will share nodes. For cracking, separate nodes on the elements on either side of the crack can be generated by identifying the seam. This is only feasible in the case of separate cases. The FE model mesh generated approximately 26801 number of C3D10M elements. With the C3D10 M elements, a significant improvement in the contact resulting with the above combination can be noted. Ideal uses include surface-to-surface modeling or surface contact with direct enforcement. Fig. 5 is a FE model excited the incident to get reflected and transmission signals of the crack.

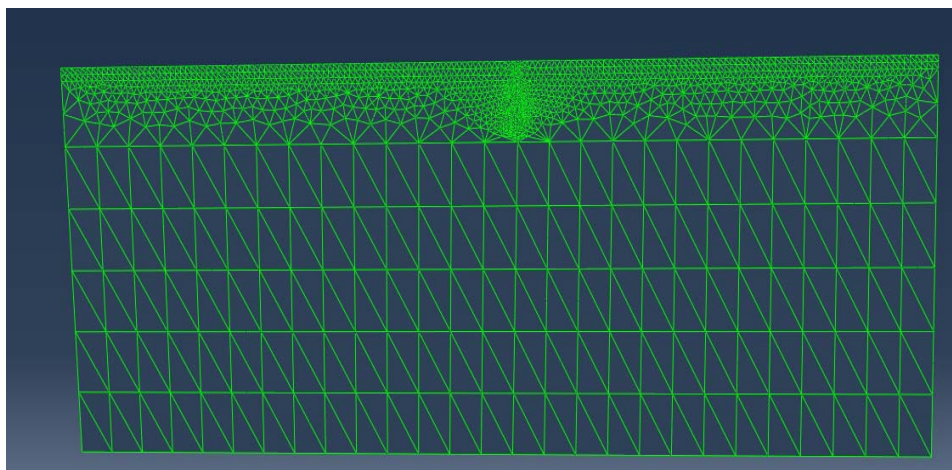


Fig. 6 FE model presentation of the crack design and C3D10m elements

### E. Nonlinear Ultrasound Technique

The nonlinear system RITEC-SNAP-5000 as shown in Fig. 7 was used for nonlinear ultrasonic measurements in this study. Subharmonic generation was achieved using SS with a partially contacted crack on the edge surface. The number of excitation signal cycles increased to six cycles to minimize the frequency bandwidth in the frequency domain. This ensures that the second harmonic produced does not interfere with the frequency-excitation components of the frequency domain. Excitation signals were applied to the piezoelectric transducer to produce a WW signal. A dyad of transducers was placed on both side of the mild steel specimen and a 2.25 MHz

piezoelectric transducer was used as an impulse transmitter (setting as 6 cycles in this experiment) Input signal as sin wave and converted to the Hamming window signal resulting in higher harmonic (fundamental frequency) and 5MHz piezoelectric transducer was used as a receiver for receiving the fundamental wave (A1) in the oscilloscope. The light lubricating oil is applied to both the transducers. The scanning frequency was set from 1 to 7 MHz and following the expeditious transfer of the Fourier (FFT) signal, the frequency spectrum of the transmitted signal can be obtained. Then, the amplitude of the incident and transmitted A1 signal can be quantified.

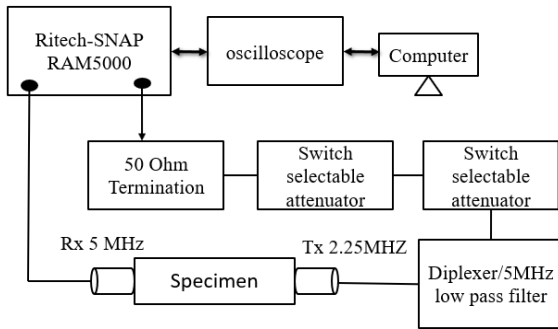


Fig. 7 Frequency buster RAM-5000 experimental system

### III. RESULTS AND DISCUSSIONS

The time domain diagram is used to measure the peak value to determine the waveform of the I, R, and T signals. The incidents reflected and transmitted simple ASF modes, or A1 modes, are classified as IA1, RA1, and TA1. Fig. 8 displays FE simulation of incident/reflected and Fig. 9 displays transmitted ASF signals for point 60° wedge samples with crack.

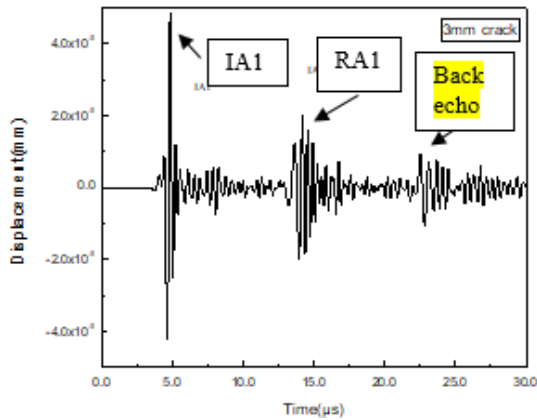


Fig. 8 The IA1 and RA1 wave of ASF mode by simulation

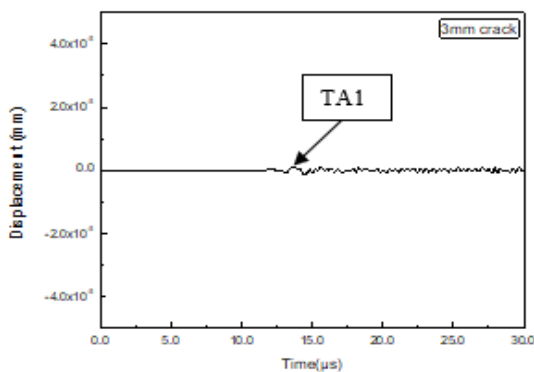


Fig. 9 The TA1 wave of ASF mode by simulation

The result indicates the distribution of A1 mode when approaching the defect ASF mode reflected/transmitted A1 mode can be observed. The same phenomenon is described by a laser ultrasound and Figs experiment. You will also find the same conversion mode as the ASF

mode spreads to the defect in Figs. 10 and 11. The calculation of the experiment is well correlated with the FEM study. The results show the A1 mode RC and TC at 60° wedge. The result shows that the depth of the defect is roughly proportional to the RC but inversely proportional to the TC.

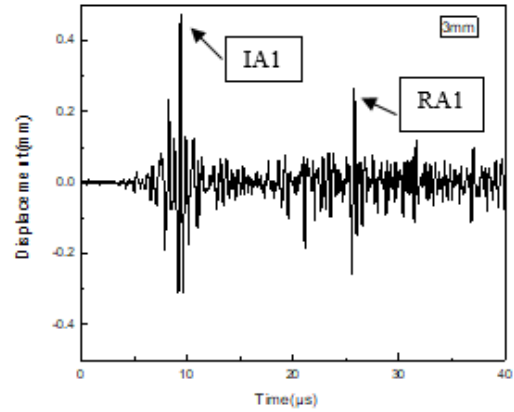


Fig. 10 The IA1, RA1 wave of ASF mode by experiment

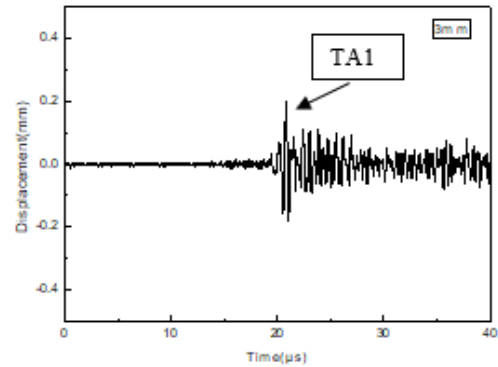


Fig. 11 The TA1 wave of ASF mode by experiment

The non-linearity of the signal obtained directly from the oscilloscope using RITECH 5000 as the Bruster frequency to obtain subharmonics for the transmitted signal is shown in Fig. 11. Due to the 6-cycle excitement, more than one wave packet appears in the received signal. The advent time of the first wave packet is 32.5 μs, which is consistent with the theoretical velocity of the dispersion curve observed by the ASF wave modes. Signals after processing for nonlinear material are seen only in Fig. 12, which are in the time domain at a fundamental frequency and at a double frequency. It is conspicuous that the second harmonic wave arriving at the same time as the fundamental wave frequency was 2.25MHz ( $f_1$ ) and second harmonic was at 4.5 MHz ( $f_2$ ), which is double the fundamental frequency ( $2xf_1$ ) and third harmonics are obtained at 6.75 MHz ( $3xf_1$ ).

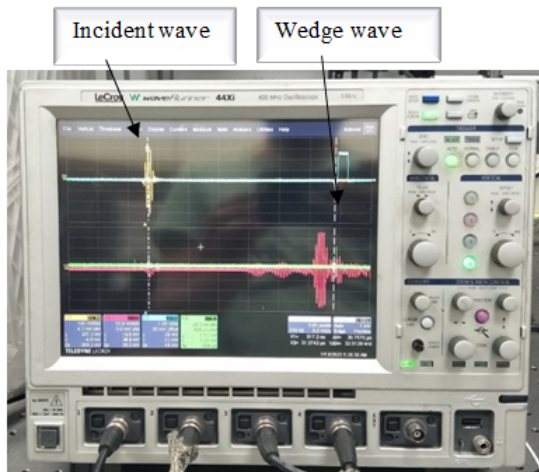


Fig. 12 The transmitted signal of ASF mode by RITECH 5000

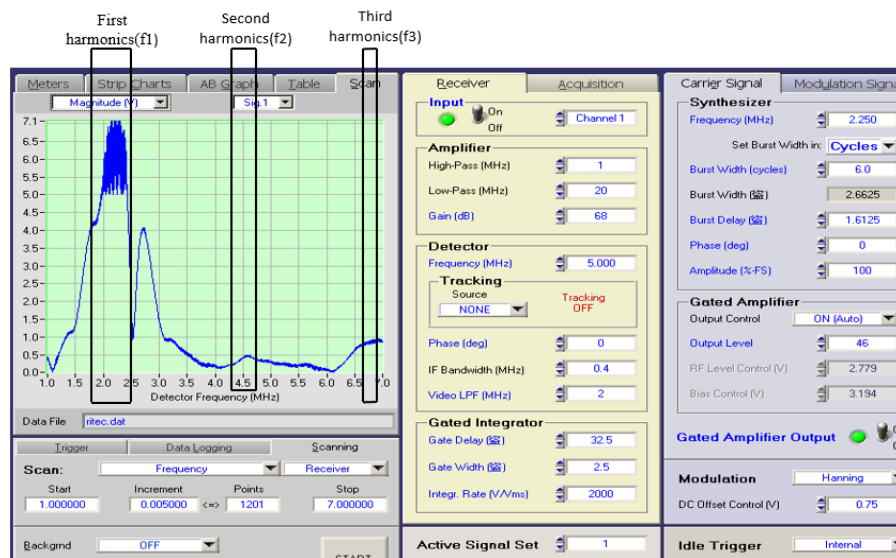


Fig. 13 Subharmonic signal of ASF mode by RITECH 5000

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## IV. CONCLUSION

In this paper, the distributed behaviors of the ASF modes along the wedge tip crack were measured using the LUT. The results collected from the traditional method of pitch-catch based on the distribution of the ASF mode are investigated systematically. Based on the results observed, the following conclusions were drawn.

- The IA1, RA1 and TA1 signals energy of the amplitude are observed on wedge surface with a crack.
- Simulation and experiments by LUT of ASF modes propagation behaviors in wedge surface are successfully done.
- Non-linearity of crack materials can be investigated by using sub harmonics function by using RITECH 5000.
- In the future, a comparison of simulation and experimental with different crack lengths need to be investigated.