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STUDY OF SECOND HIGHER -HARMONIC WAVES GENERATION CAUSED BY FATIGUE CRACKS: THE MEASUREMENT OF RESONANT HIGHER HARMONICS AND NATURAL VIBRATIONS CAUSED BY CRACKS

Kosuke Kanda[1], Shan Lin
Central Research Institute of Electric Power Industry
Kanagawa, Japan

ABSTRACT

Nonlinear ultrasonic waves, including higher -harmonic (HH)-waves, are likely to be applied in non-destructive evaluations of power plants. We first constructed a system to measure the frequency response characteristic of ultrasonic waves and experimentally investigated the mechanism of second HH generation caused by fatigue cracks. The system comprised of three-dimensional laser Doppler vibrometer (3D-LDV) to obtain contactless and local measurements. The features of 3D-LDV are suitable for crack-induced scattered ultrasonic vibration measurements. Subsequently, by sweeping the input frequency, we measured the frequency response characteristic caused by fatigue cracks using the system and consequently obtained a natural frequency from the characteristic. Further, we measured the frequency response characteristic of the second HH using the same system and consequently, confirmed that the second HH resonated when its frequency corresponded to the natural frequency caused by the cracks. Additionally, we analytically revealed that the resonant second HH was generated from natural vibration and nonlinearity.

Keywords: ultrasonic testing, nonlinear ultrasonic, higher-harmonic wave, natural vibration, fatigue crack

NOMENCLATURE

f Frequency

$F_c(f)$ Response Fourier amplitude in the measurement region with cracks when the frequency is f

$F_o(f)$ Response Fourier amplitude in the measurement region without cracks when the frequency is f

1. INTRODUCTION

Ultrasonic testing (UT) is widely applied for inspecting power plants. However, the detection of micro and closed cracks becomes challenging with UT. Hence, nonlinear ultrasonic waves, which are higher -harmonic (HH), sub-harmonic (SH), and sum difference harmonic, are likely to be applied in a non-destructive evaluation (NDE). For example, Kim et al. quantitatively characterized a damage state in the early stages of fatigue using HH [1]. Further, Ohara et al. showed that SH images provide an accurate length of partially closed cracks [2]. Nonlinear UT (NLUT), including these techniques, may help achieve an NDE that is more sensitive, but the mechanism of nonlinear ultrasonic generations caused by cracks remains unclear. When NLUT is applied to the actual equipment, we must understand the mechanism not to remain accidental undetected. In recent researches, Solodov showed that the effect of local defect resonance in thin plates in the generation of nonlinear vibrations [3]. Further, Maruyama et al. numerically showed that the ultrasonic frequency property caused by cracks is highly associated with SH generation [4]. These results showed that

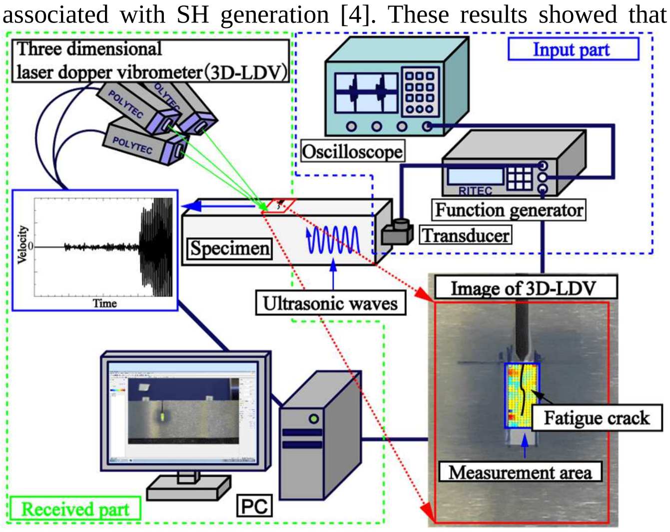

FIGURE 1: SCHEMATIC OF EXPERIMENTAL SETUP

[1] Contact author: k-kosuke@criepi.denken.or.jp

nonlinear ultrasonic may be generated from the ultrasonic frequency response characteristic caused by cracks. However, the hypothesis has not been experimentally validated. In this study, we experimentally investigate the mechanism of second HH generation caused by fatigue cracks.

2. EXPERIMENT

We constructed an experimental system to measure the frequency response characteristic of ultrasonic waves (Fig. 1). The system composed of a function generator (RITEC RPR-4000) for generating signals to the input transducer; oscilloscope (Tektronix TDS5034B) displays the input signals; the transducer (KGK 5C10N-F, 5 MHz central frequency or KGK 2C10N-F, 2 MHz central frequency) inputs ultrasonic waves to the specimen; specimen (SUS304 $260 \times 60 \times 50$ mm^3) has fatigue cracks; three-dimensional laser Doppler vibrometer (3D-LDV: Polytec PSV-500-3D) measures the velocity vectors of scanning points; and computer controls the 3D-LDV, records the time histories of the velocity, and analyzes the recorded data. The 3D-LDV measures velocity vectors in a contactless manner and locally. The features of 3D-LDV are suitable for measuring scattered ultrasonic vibrations caused by the cracks because the scattered waves include longitudinal waves and transversal waves, although the incident waves are pure longitudinal waves or transversal waves.

2.1 Frequency response characteristic of ultrasonic caused by fatigue cracks

We investigated the frequency response characteristic of the ultrasonic waves caused by fatigue cracks. To extract the frequency response characteristic caused by the cracks from the entire system characteristic, we prepared results of specimen with fatigue cracks and an immaculate one. The sizes of the specimens are shown in Fig. 2. To obtain the characteristic curve, frequency sweeping under the frequency region from 3 MHz to 6 MHz was performed. Following a flowchart shown in Fig. 3, we measured the characteristic as nondimensional response amplitudes caused by the cracks. An example of data processing according to the flowchart is shown in Fig. 4. The generation of resonance phenomenon caused by the fatigue cracks was observed. Further, we obtained the natural frequency at which the resonance was generated approximately 3.9 MHz. The phenomenon shows that the existence of cracks invokes natural vibration.

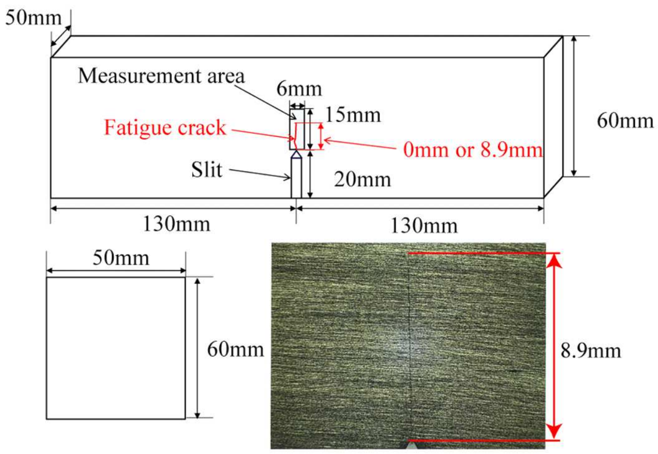

FIGURE 2: SPECIMEN SIZE

2.2 Relation between second higher-harmonic wave generation and the frequency response characteristic caused by cracks

Herein, we investigated the relation between the second HH wave generation and the frequency response characteristic caused by cracks. By sweeping the input frequency to set the frequency of the generated second HH waves around the natural frequency caused by the fatigue cracks and by following the flowchart (Fig. 3), we obtained the second HH frequency response characteristic as nondimensional response amplitudes. Based on the results, we confirm that the second HH waves resonate when their frequency corresponded to the natural frequency caused by the cracks. The phenomenon is called second HH resonance.

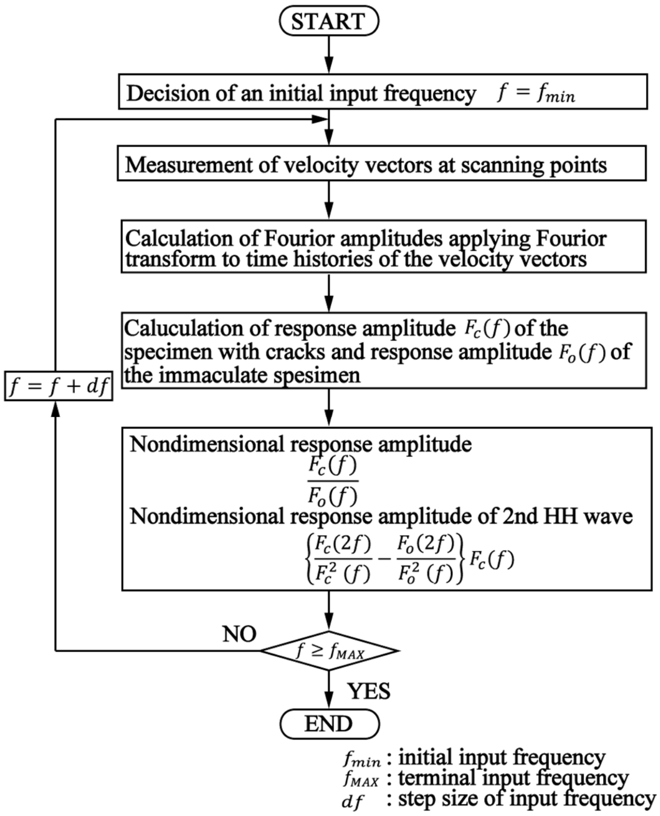

FIGURE 3: FLOWCHART FOR CALCULATING THE FREQUENCY RESPONSE CHARACTERISTIC

3. CONCLUSIONS

By constructing a system to experimentally measure the frequency response characteristic of ultrasonic waves, we estimated the linear and nonlinear frequency response characteristic caused by fatigue cracks. Therefore, we confirm that the natural vibration and second HH resonances are generated from the cracks.

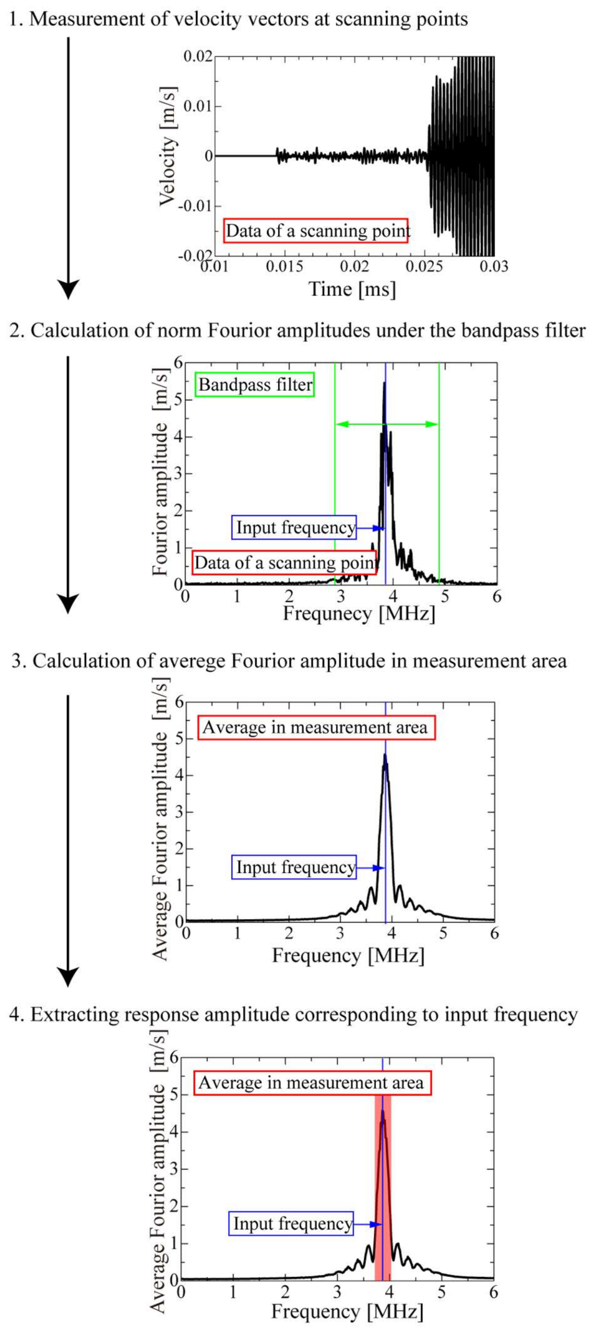

FIGURE 4: EXAMPLE OF DATA PROCESSING FOLLOWING THE FLOWCHART (THE CASE WHERE THE INPUT FREQUENCY IS 3.9 MHz)

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