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# NONLINEAR HARMONIC IMAGING OF SOLIDS USING NONLINEAR IMMERSION ULTRASONICS

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## ABSTRACT

*Nonlinear ultrasonics has been shown to be sensitive to microscale damage, lattice defects, and microstructural changes induced due to thermal and mechanical loading. The most well-known technique for evaluating the nonlinear properties of solids is harmonic generation. However, traditionally, harmonic generation has been limited to contact transducers and single point measurements.*

*The present work explores the use of immersion piezoelectric transducers to measure the nonlinearity parameter of solids immersed in a fluid. This enables us to perform a nonlinear immersion C-Scan, which can be further used to localize defects or nonlinear sources. Nonlinear harmonic imaging of two cases will be demonstrated. The 1st case uses a low carbon steel bar subjected to full reversed bending, thus creating localized plastic zones. The 2nd case uses A302 steel bar subjected to plastic deformation and local heat treatment. Harmonic imaging of both cases show that nonlinear sources can be localized. The challenges which act as roadblock going towards to a complete tool are also highlighted.*

Keywords: nonlinear ultrasonics, immersion C-Scan, harmonic imaging

## 1. INTRODUCTION

There has been considerable interest in detecting and characterizing small scale damage or microstructural changes induced due to thermal and mechanical loading. The need for this increase drastically, especially progressive damage mechanisms such as fatigue damage. The defect initiation and growth are very slow over time, and catastrophic failure occurs at an accelerated rate. This also highlights the need to detect such defects much early on the life of the sample. However, most nondestructive techniques used for defect detection are not sensitive to such defects.

Recent progress in the last 3-4 decades in terms of using finite amplitude ultrasonic waves for detecting small scale damage have been successfully demonstrated [1]. Nonlinear ultrasonics employs finite amplitude waves to interact with microstructural features to generate high harmonics. The higher harmonics are integer multiples of the fundamental frequency, and their amplitude is proportional to the lattice defects and microscale damage they interact with. Previous research involves comprehensive investigations into modeling the harmonic response from lattice harmonicity, dislocation, persistent slip and Luder bands, up to microcracks [1, 2, 3]. This type of modeling enables us to quantify physical parameters which change over the fatigue life of the sample.

However, one of the disadvantages of using nonlinear ultrasonics is the complex calibration techniques which accompany the experimental setup. The use of contact-based transducers limits any scanning ability. The present work demonstrates the use of commercial immersion transducers to measure the higher harmonics generated in a solid, immersed in a fluid medium. The use of piezoelectric calibrations helps us determine absolute harmonic amplitudes, paving way to measure the absolute nonlinearity parameter. Further, the technique has also been used for harmonic imaging, i.e. beta-C-Scan, which can map specific harmonics. The harmonic scanning method is used to test two cases, especially for localization of nonlinear sources.

## 2. MATERIALS AND METHODS

Before carrying out the harmonic scans, it is important to calibrate the immersion transducers and carry out a beta measurement of the fluid. Fig. 1 shows the experimental setup for calibration. The immersion transducer is pointed to the water-fluid interface to act as free surface, i.e. we select -1 reflection coefficient to eliminate any harmonic generation. Measuring the input and output current using the current probes, we can determine the power, and thus the transfer function $K_R$:

$$K_R = \sqrt{{P_{out}}/{P_{avail}}} \tag{1}$$

Further, we can calculate the calibration function using the formula:

$$H(\omega) = \sqrt{{Z_L}/{(\omega^2 \rho c_L A K_R)}} \tag{2}$$

Notice the calibration function has the unit (m/amp), therefore giving the ability to convert a measured signal from “ampere” to displacement amplitude in “meter”. The fluid chosen in this case is distilled water, whose velocity and attenuation characer5istics are well known. The receiver frequency is chosen such that its positioned centrally around the 2nd harmonic of the fundamental frequency.

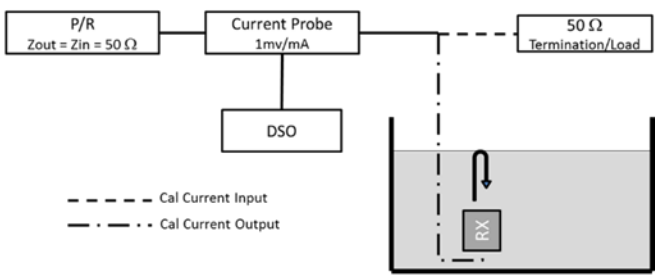


**FIGURE 1:** PERCENTAGE OF PAPERS THAT SHOULD BE FORMATTED CORRECTLY

The calibrated transducer can now be used to measure the beta of fluid using the experimental setup shown in Fig. 2. The formula for measuring the beta of the medium is given by the equation:

$$\beta = {4A_2}/{(A_1^2 k^2 x)} \tag{3}$$

Where the A1 and A2 are the fundamental and 2nd harmonic displacement amplitudes.

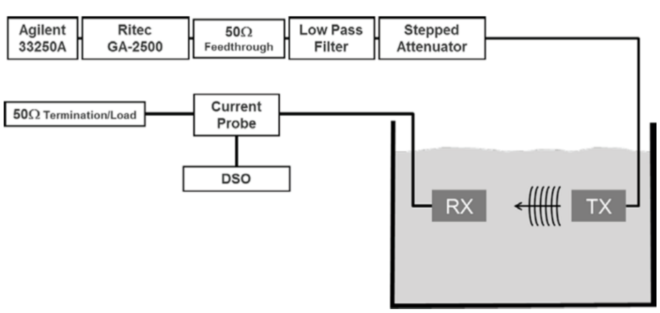


**FIGURE 2:** PERCENTAGE OF PAPERS THAT SHOULD BE FORMATTED CORRECTLY

The beta measured using this technique for distilled water after correction for attenuation was 3.5 ± 0.11. Diffraction could also be included, but the distance between the transmitter and receiver was chosen within the near field distance, where diffraction has very little effect.

## 3. RESULTS AND DISCUSSION

To obtain harmonic images and localize defects, it’s important to have the right sample. If the local nonlinear response is similar to the rest of the sample and any variation is very small, then it becomes challenging to measure such local differences. To induce higher nonlinearity, a low carbon steel plate of 6.25mm thickness was subjected to 3 point flexural loading. It was plastically deformed in one direction, and the load was released, and the sample was flipped and bent again till it became flat. This plastic deformation is supposed to induce high dislocation density, and other lattice defects which can give rise to higher harmonic content. To test this theory, the sample was scanned using 5MHz fundamental transmitter and 10MHz receiver. The transducer alignment is very crucial in scanning, and to reduce the error, point by point scans were carried out. This also limits the spatial resolution of the scan itself.

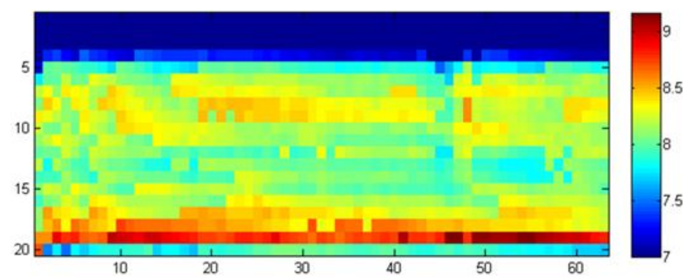


**FIGURE 3:** PERCENTAGE OF PAPERS THAT SHOULD BE FORMATTED CORRECTLY

Fig. 3 shows the fundamental signal variation as a function of spatial position. There are location os drop in amplitude, especially a horizontal zone. Apart from this, the sample looks nominally uniform. The 2nd harmonic was also extracted using the signal processing methods reported earlier. The 2nd harmonic was further divided by the fundamental square, i.e. $A_2/A_1^2$ to get the 2nd harmonic ratio A2R, which would be directly proportional to the beta in that path.

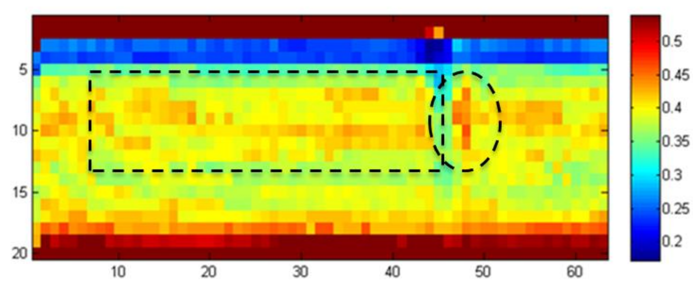


**FIGURE 4:** PERCENTAGE OF PAPERS THAT SHOULD BE FORMATTED CORRECTLY

The A2R value can be seen to be vary similar to the A1 value, but of particular interest is the 2 zones marked in the figure. The circular region is near the center loading of the 3-point fixture, where maximum stresses are expected. A drop in amplitude due to a small bump of the surface is followed by a strong increase in harmonic ratio due to increase in higher harmonic content. Similarly, the rectangular zone also shows increase in higher harmonic content.

## 4. CONCLUSION

The harmonic scan images essentially highlight the advances in imaging of nonlinear sources. The use of calibrated transducers will help in measuring the absolute nonlinearity parameter of a solid immersed in a fluid, and could further lead to a beta Scan, or nonlinear harmonic C-Scan. Such a capability will be vital for advancing and utilizing the nonlinear capabilities for field implementation.


## ACKNOWLEDGEMENTS

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