46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-1234

USING NONLINEAR ULTRASOUND TO QUANTIFY THE MATERIAL STATE OF PIPELINE STEEL SPECIMENS WITH MECHANICAL DEFECTS

Denis Pfeifer[1], Jin-Yeon Kim, Laurence Jacobs
Georgia Institute of Technology
Atlanta, GA

ABSTRACT

The current state of the art in determining the remaining fatigue life of a dented pipeline is to use FE- and empirical models that were created based on known, artificial dents. However, this approach does not account for the actual material state, which is influenced by a combination of damages.

The objective of this research is to determine the actual current state of fatigue of a dent in a pipeline by using nonlinear ultrasound (NLU) as a material sensor to detect the gross effect of accumulated dislocations. The physical effect that is monitored by the nonlinear ultrasonic measurement is the generation of higher harmonic frequencies in the initially monochromatic ultrasonic waves propagating in the component. The degree of nonlinearity is quantified with the acoustic nonlinearity parameter, β, which is an absolute, measurable material constant. The first step is to take baseline measurements to determine fabrication, pre-strain and material intrinsic influences in the material specimen made of X42, X52 and X60 pipeline steel. Then pre-strain is applied to simulate a dent. At different stages during the materials fatigue life, the straining of the material is interrupted to perform NLU measurements. The results are expected to show an increasing nonlinearity with increasing fatigue.

Keywords: nonlinear ultrasound, nondestructive evaluation, second harmonic generation, fatigue life, pipeline, dent

NOMENCLATURE

β	absolute nonlinearity parameter
β'	relative nonlinearity parameter
c	wave speed
f	frequency
ω	angular frequency
x	propagation distance
A_1	amplitude of the fundamental frequency wave
A_2	amplitude of the second harmonic wave
θ_w	wedge angle
NLU	nonlinear ultrasound

1. INTRODUCTION

If a pipeline fails it is mostly due to mechanical damage or corrosion. When a pipeline is damaged, a “fitness-for-purpose” assessment is performed in order to determine if and when a repair is necessary. Since there is not one perfect method to assess the severity of a defect, there exists a pipeline defect assessment manual (PDAM) that lists a number of methods to assess the different defects. [1]

The methods in the PDAM, which were developed mostly before 1990, are often (semi-)empirical and are only valid for the range of use cases that they have been tested for in full scale tests. These models only consider artificial damage. However they ignore many properties of the actual damage. Most of the work nowadays concentrates on validating the methods’ applicability for modern materials, use cases and the development of FE-models. However, there is little fundamental research to develop new, better methods. [2]

This research aims to use nonlinear ultrasound as a material sensor to measure the material state of a dent (while in the future of this project also dents with a gouge and/or corrosion will be examined). Nonlinear ultrasound has proven to be sensitive to the early symptoms of fatigue damage such as dislocations, before microcracks appear [3], [4]. The measured physical quantity is the amplitude of the second harmonic frequency which stands in direct correlation with the material’s nonlinearity. This effect is quantified by the acoustic nonlinearity parameter, β, which is an absolute, measurable material constant. One part of this research is the determination of the effects of different steel fabrication processes and levels of pre-strain on order to differentiate them from the actual fatigue damage. This will provide a better starting point for fatigue life prediction models. Then the behavior of the pipeline material during its fatigue life is examined by taking further NLU measurements while damage is induced in the material specimens. These measurements will help to characterize the material properties for different pipeline steels and to classify the state of a material. This information can be used in future research as input for material models to estimate the remaining fatigue life of a dented pipeline.

---

[1] Contact author: dpfeifer@mail.de

2. MATERIALS AND METHODS

This research project uses NLU to examine different pipeline steel specimens with mechanical defects.

2.1 Pipeline steels and defects

Specimens of three different pipeline steel types will be examined, namely X42, X52 and X60 steel. The number refers to their minimum yield strength of 420,000, 520,000 and 600,000 PSI, respectively. After taking baseline measurements, an increasing amount of plastic deformation is introduced into the specimen (which results in an increased dislocation density), interrupted by further measurements. This material damage simulates the plastic deformation introduced by a plain dent. A plain dent is a dent which bends the pipeline wall without reducing its wall thickness.

2.2 NLU measurements

A monochromatic ultrasonic burst signal is sent through a wedge that is attached that is attached to the tested specimen.

The burst signal is sent by a function generator at the center-frequency of the transducer of 2.1 MHz. It is amplified to 800 mV peak-to-peak voltage and has a length of 20 cycles. The wedge angle θ_w is such that a Rayleigh wave is generated in the specimen.

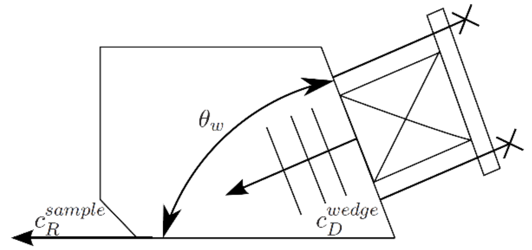

Figure 1: Rayleigh wave generation wedge and transducer [6]

The Rayleigh wave then propagates along the surface of the specimen and the leaking longitudinal waves are measured using an air-coupled transducer. The measured signal is then post-amplified and averaged over 512 signals.

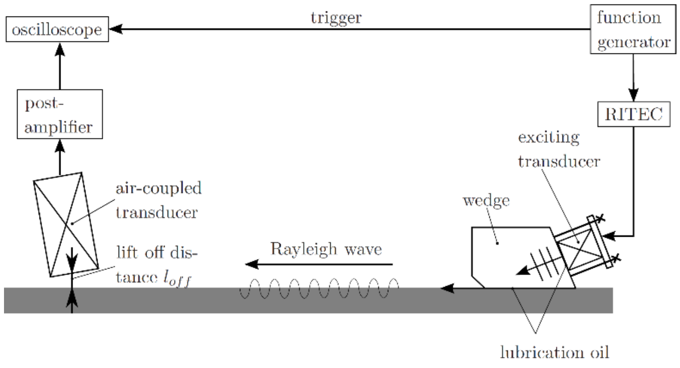

Figure 2: NLU measurement setup [6]

A typical measurement (in the frequency domain) is depicted in figure 3.

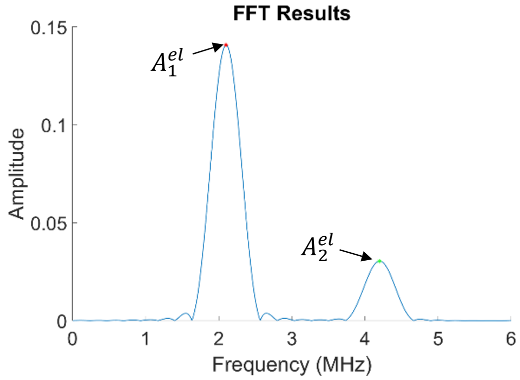

Figure 3: FFT of typical measurement at one propagation distance

The nonlinearity parameter β can be calculated as

$$\beta = 8\frac{A_2}{A_1^2}\frac{c^2}{\omega^2 x}, \tag{1}$$

where A_2 is the amplitude of the second harmonic, A_1 the fundamental frequency, x the propagation distance (between source and receiver), c the plane wave speed, and ω is the angular frequency [5]. However, the amplitudes A_1 and A_2 can't be measured directly. The actually measured amplitudes A_1^{el} and A_2^{el} (index el for electric signal) depend on many factors other than the amplitudes of the leaking p-waves. Some of those factors are the quality of the oil coupling between the transducer and the specimen, the lift off distance and the frequency response of the transducers. [7].

Thus, the relative nonlinearity parameter β' is introduced. It is determined

$$\beta' \propto \frac{A_2^{el}}{\left(A_1^{el}\right)^2 x} \propto \beta \text{ [5]}. \tag{2}$$

The measuring procedure is repeated for several propagation distances. The ratios $\frac{A_2^{el}}{\left(A_1^{el}\right)^2}$ are plotted over the propagation distance and a linear fit is created. The slope of this fit corresponds to the relative nonlinearity parameter β' and it is proportional to the absolute nonlinearity parameter β.

3. RESULTS AND DISCUSSION

The NLU technique is validated before beginning the measurements on the pipeline steel specimens.

The investigated material is 9%Cr ferritic martensitic steel and the specimens are thermally aged at 650°C for different holding times [6]. In figure 4 the result of the β'-measurements is shown. The measured relative β'-values are normalized by the mean β'-value of the untreated specimen. In blue the mean β'-values and error range are plotted as determined in [6]. The red data points for the unmodified specimen and the specimen, that was heat-treated for 1000 h, are results from measurements for this research in order to validate the NLU technique.

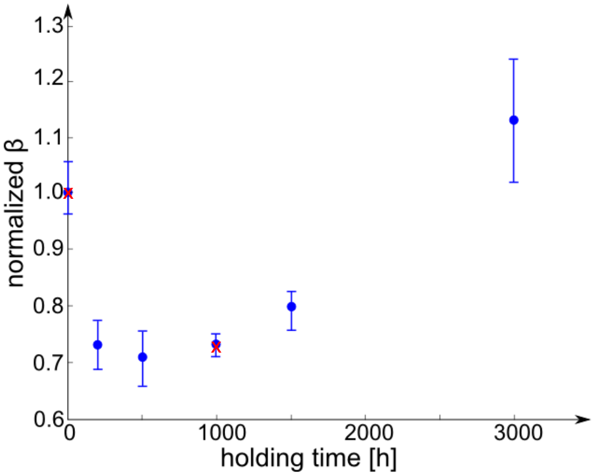

Figure 4: β'-measurements for different holding times [6]

The explanation why the nonlinearity drops is that during the annealing process the amount of dislocations in the material sinks. (The rise after 1000 h of holding time is due to the formation of the formation and growth of precipitates.) [6]

The results from the validation measurements match the results established in [6] very closely.

4. CONCLUSION

As shown in a similar research project and validated in this project, it can be concluded that the nonlinearity parameter is sensitive to microstructural changes such as dislocation density and precipitates.

The pipeline steel specimens in this research are subjected to plastic deformation to simulate a plain dent, which should increase the dislocation density in the material. Since it has been proven by previous research that NLU is able to detect these changes, it is expected to see a rising ultrasonic nonlinearity with increasing deformation. The future course of this research is to perform the measurements as described in this paper and to discuss the results.

ACKNOWLEDGEMENTS

This work was partially supported by the U.S. DOT Pipeline and Hazardous Materials Safety Administration (PHMSA) under contract 693JK31850006CAAP.

Furthermore, this project received funding by THE SCHAUFLER FOUNDATION.

REFERENCES

[1] Andrew Cosham, Phil Hopkins. “The effect of dents in pipelines—guidance in the pipeline defect assessment manual”, International Journal of Pressure Vessels and Piping, Volume 81, Issue 2 (2004): 127-139. doi.org/10.1016/j.ijpvp.2003.11.004.

[2] Macdonald, K.A., Cosham, A. “Best practice for the assessment of defects in pipelines – gouges and dents”, Engineering Failure Analysis, Volume 12, Issue 5 (2005): 720-745. doi.org/10.1016/j.engfailanal.2004.12.011.

[3] Hikata, A., Chick, B.B., Elbaum, C. “Dislocation contribution to the second harmonic generation of ultrasonic waves”. Journal of Applied Physics, Vol.36 (1965): 229-236

[4] Matlack, K. H., Kim, J.Y., Jacobs, L.J., Qu, Jianmin, “Review of second harmonic generation measurement techniques for material state determination in metals”, Journal of Nondestructive Evaluation (2015), DOI 10.1007/s 10921-014-0273-5.

[5] Herrmann, J., Kim, J.-Y., Jacobs, L. J., Qu, J., Littles, J. W., and Savage, M. F., “Assessment of material damage in a nickel-base superalloy using nonlinear rayleigh surface waves,” Journal of Applied Physics, vol. 99, no. 12, (2006).

[6] Marino, Daniel, Kim, Jin-Yeon, Ruiz, Alberto, Joo, Young-Sang, Qu, Jianmin, Jacobs, Laurence J., “Using nonlinear ultrasound to track microstructural changes due to thermal aging in modified 9%Cr ferritic martensitic steel”, NDT & E International, Volume 79, (2016): 46-52, doi.org/10.1016/j.ndteint.2015.12.002.

[7] Thiele, Sebastian, Kim, Jin-Yeon, Qu, Jianmin, Jacobs, Laurence J., “Air-coupled detection of nonlinear Rayleigh surface waves to assess material nonlinearity”, Ultrasonics, Volume 54, Issue 6 (2014): 1470-1475, doi.org/10.1016/j.ultras.2014.04.020.