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IEEE
2022

Mustonen , J A , Suorsa , J F , Iablonskyi , D , Klami , A , Salmi , A & Haeggström , E 2022 , Localizing Fouling in Water-Filled Pipe with Laser-Induced Non-Axisymmetric Guided Waves . in 2022 IEEE International Ultrasonics Symposium (IUS) . IEEE , 2022 IEEE International Ultrasonics Symposium (IUS) , Venice , Italy , 10/10/2022 . https://doi.org/10.1109/IUS54386.2022.9957524

http://hdl.handle.net/10138/354159
https://doi.org/10.1109/IUS54386.2022.9957524

publishedVersion

Localizing Fouling in Water-Filled Pipe with Laser-Induced Non-Axisymmetric Guided Waves

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Abstract— **Effective fouling quantification and localization is an unsolved industrial challenge. As in non-destructive evaluation, fouling could be quantified using traditional transducer collars, which also simplify the structure to a 1D-system. In this case the radial information of the location of the fouling is lost. We localized different kinds of fouling in a 3D-system using laser-induced point-excitation and non-axisymmetric guided waves to provide experimental input for an AI-based detection algorithm. Results show that only echoes from those paths intersecting the fouling were altered (decreased amplitudes, time of flight shifts). By amalgamating information from several circumferential paths, the fouling can be located in the pipe.**

Keywords— Guided waves, fouling detection, laser-ultrasonics

I. INTRODUCTION

Fouling is an industrial challenge, causing both economic losses and negative environmental impact [1]. Traditional fouling detection is based on changes in heat transfer coefficient, mass flow rates, pressure drops and temperature [2], requiring impractical long and local steady state measurements. In the field of non-destructive testing (NDT), ultrasonic guided waves (UGWs) provide industrially applicable solutions for finding structural defects [3]. Therefore, it has been suggested that UGWs could be used to detect fouling [4]: an additional fouling layer attached on the wave guide alters the fd-product, and therefore the velocities of the propagating modes are changed. Moreover, the fouling load allows sound energy to leak from the wave guide, resulting in decreased amplitudes in the measured UGWs. In the literature, the UGW-based approach has been tested with AI-driven detection algorithms with promising results [5, 6].

In pipeline structures, the transmitting and receiving transducer sensors are coupled around the circumference of the pipe, during UGW measurements [7]. While providing an efficient and selective UGW excitation, the transducer collars reduce the structure into a 1D-system, which means losing the radial information of where the fouling is located. Moreover, the usage of transducer collars requires contact coupling on the pipe, which may not be possible in all practical cases.

In the study, the effects of different fouling configurations on a water-filled pipe were investigated by using high-order circumferentially propagating Lamb waves. If the propagation path traversed any fouling, the measured signal became altered. Steel pipe with water mimics the industrial relevant conditions and challenges, such as attenuation due to the leaky Lamb waves. By comparing measured signals from different fouling configurations, effects from different fouling parameters could be distinguished. The method could potentially be utilized to provide experimental input for artificial intelligence (AI) - based fouling localization and quantification algorithm.

II. MATERIALS AND METHODS

A. Experimental setup

A custom-made Python3-program with Digilent WaveForms® was used to control the measurement setup. Analog Discovery 2® was connected to a laser diode driver module (PCO-7120) and to a laser-diode (SPL PL90_3, wavelength: infrared 905nm). The light was collimated with a mounting hardware and guided onto the water-filled pipe (Ø=60mm, thickness: 1mm) with an optical fiber, enabling a point-like excitation. The laser pulse (length: 60ns, energy: 10μJ, radius: 1mm) generated a point-like, thermo-elastic, broadband excitation, creating multiple different UGWs that propagated on the pipe with different frequencies and along different paths. If the propagation path traversed fouling, the corresponding echo in the recorded signals was altered. The pick-up transducer (Ø=20mm) was dry-coupled to the opposite site of the pipe (180°, distance along pipe: 22cm). The measured ultrasonic signals were amplified with a 60dB pre-amplifier (Ultrasonic preamp Panametric 5660C) and recorded with a 16-bit Picoscope (series 5000). Signals were averaged 5000 times before saving.

Funding was provided by the Academy of Finland (grant 336019).

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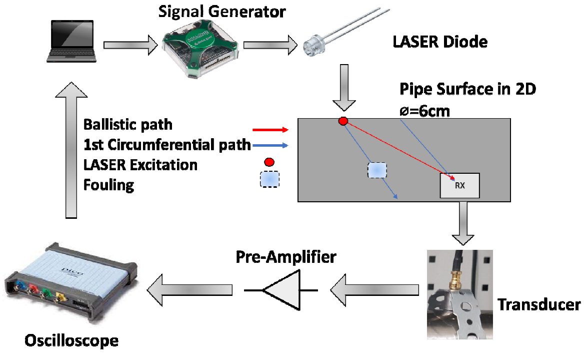

Fig. 1. Schematic of the setup. Custom Python3-program with Digilent WaveForms® software control Analog Discovery 2®, which is connected to a laser diode. The diode produces a laser pulse that generates a spherical, ultrasonic wavefront in the water-filled pipe, creating multiple different modes propagating along different paths. UGWs are recorded with an ultrasonic transducer and the recorded signals pre-amplified before digitizing them with a Picoscope.

B. *Fouling configurations*

Five different fouling configurations were investigated (Fig. 2), denoted 'Clean', and 'Foul01-04'. 'Clean' refers to the case without fouling; 'Foul01' is tape fouling (40 x 40 x 2 mm3) on the left corner; 'Foul02' is same tape fouling placed on the right corner; 'Foul03' features soft adhesive pads with same size and location as 'Foul01', 'Foul04' is smaller size version of the adhesive pads case (20 x 20 x 2 mm3) on the left corner (fig. 2). All configurations containing fouling are compared to the clean case. First, the no fouling case was measured, then all fouling cases. This was repeated five times, resulting in 25 signals.

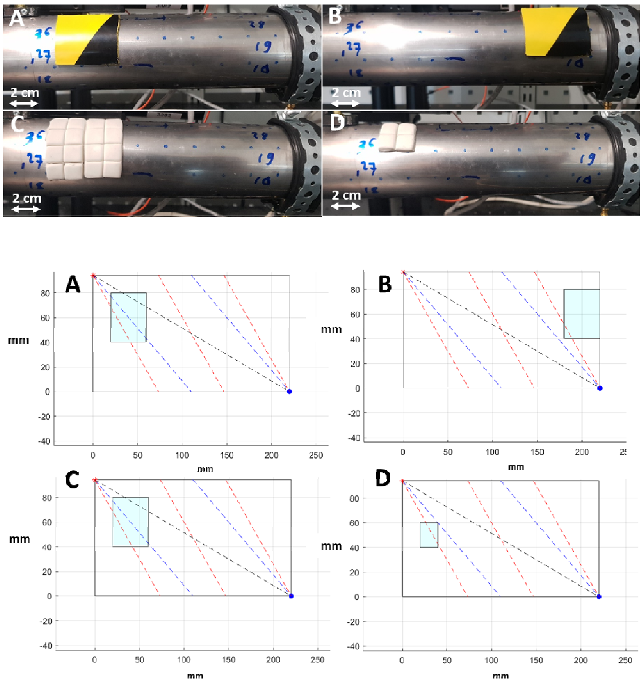

Fig. 2. Fouling configurations (upper) and a visualization of the first propagation paths (below). Foul01 (A) and Foul02 (B) configurations feature the same fouling (40 x 40 x 2 mm3) but located in different places. Foul01 and Foul03 (C) are the same size of fouling but made from different material (hard and soft). Foul03 and Foul04 (D) are from same material but different size fouling. All configurations are compared to a pipe without fouling.

C. *Analysis*

Different propagation paths vary in length, resulting echoes with different time-of-arrivals (ToAs) in signals measured in time. By analyzing these echoes from different paths, different fouling configurations could be distinguished from each other. The signals were filtered with a tight two-sided infinite impulse response (IIR) filter with a bandwidth of 80 – 120 kHz (band-pass). First, the cases with fouling (Foul01-04) were compared to reference clean case. Second, signals from all fouling configurations were compared to each other to see how varying fouling parameters are resulted in the measured ultrasonic signals.

III. RESULTS

A. *Experimental results*

Fig. 3 shows averaged signals from each of the five cases. In each signals, the echo from the ballistic path and four echoes from circumferential paths were distinguishable. The signals from the different cases differed from each other, even though the changes were small. For example, in cases 'Foul01' and 'Foul03', there is fouling on the ballistic path, and therefore the amplitude of the ballistic echo in the measured signals were decreased. Conversely, in case 'Foul02', fouling was not on the ballistic path, and consequently the ballistic echo was not changed. In the first circumferential path, there is more fouling in case 'Foul02' than in 'Foul01' along the propagation path, implying that the amplitudes decreased more in 'Foul02' than in 'Foul01', as is seen in the signals. In the first echo, amplitudes in case 'Foul1' (tape fouling) decreased more than in the softer case 'Foul03' (adhesive pads fouling). Case 'Foul04' is similar to the 'Clean' case in the first three echoes, while the amount of fouling is significantly smaller in this case compared to other cases. The differences between cases are greater with higher orders of circumferential paths, implying that the propagation path is longer and the amounts of fouling in the propagation path is probably greater. These differences could be used as input for an algorithm to distinguish the cases from each other.

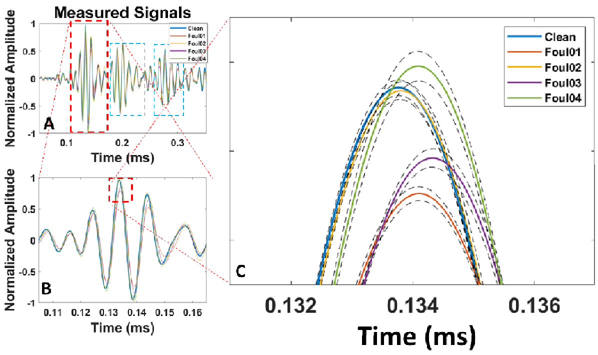

Fig. 3. Averaged signals from different fouling configurations. (A) The echoes from different paths (red is from the ballistic and blue ones are from 1-2 circumferential paths) are distinguishable in all averaged signals. (B, C) Zoomed-in first echoes from each averaged signal with deviations (± 1 standard deviation, dashed lines). The changes between signals are small, but distinguishable from the deviations.

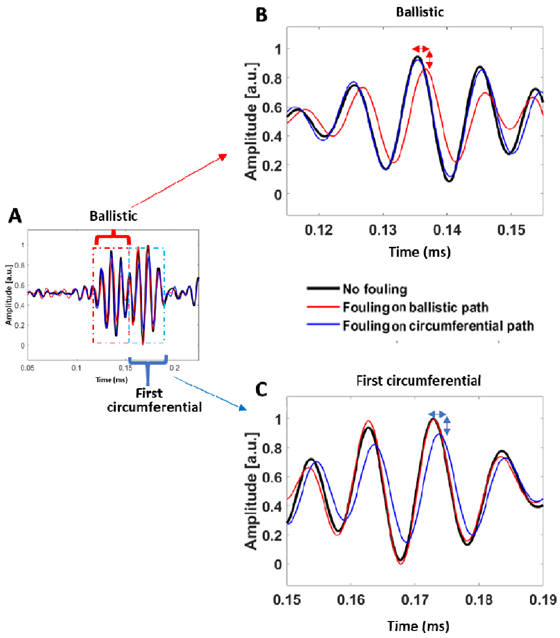

Fig. 4. (A) Signals from two different fouled patches and a reference case without fouling. (B) The first echo was altered (8µs time shift and 20% ± 4% decreased amplitude) when the fouling was situated on the ballistic path (amplitude deviation in clean cases: 0.1%). (C) When the fouling was located on the first circumferential path, similar changes (5µs time shift and 11% ± 0.1% decreased amplitude) were observed only with the second echo.

IV. CONCLUSION

According to the study, fouling size, material properties, and fouling location modify UGWs, implying that a UGW –based method could be a potential approach to detect fouling. By amalgamating information from several high order circumferential paths, the fouling could be located in the pipe accurately, but may require machine learning techniques, while differences between signals can be hard to analyze otherwise. Here, all fouling configurations were distinguished from each other based on the changes in measured ultrasonic signals. The introduced technique based on laser-induced point-excitation and non-axisymmetric guided waves could be used to provide experimental input for a machine learning –based detection algorithm.

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