Affordable and Wireless Transducer Network to Detect Fouling in Pipes

Salminen, Petteri Matias

IEEE
2022

Salminen , P M , Korsimaa , J E , Ihalainen , P S , Iablonskyi , D , Klami , A , Salmi , A & Haeggström , E 2022 , Affordable and Wireless Transducer Network to Detect Fouling in Pipes . in 2022 IEEE International Ultrasonics Symposium (IUS) . IEEE , IEEE International Ultrasonics Symposium , Venice , Italy , 10/10/2022 . https://doi.org/10.1109/IUS54386.2022.9958911

http://hdl.handle.net/10138/352084
https://doi.org/10.1109/IUS54386.2022.9958911

submittedVersion

Affordable and Wireless Transducer Network to Detect Fouling in Pipes

Petteri Salminen
Electronics Research Lab., University of Helsinki
Helsinki, Finland
petteri.salminen@helsinki.fi

Julius Korsimaa
Electronics Research Lab., University of Helsinki
Helsinki, Finland
julius.korsimaa@helsinki.fi

Peetu Ihalainen
Electronics Research Lab., University of Helsinki
Helsinki, Finland
peetu.ihalainen@helsinki.fi

Denys Iablonskyi
Electronics Research Lab., University of Helsinki
Helsinki, Finland
denys.iablonskyi@helsinki.fi

Arto Klami
Department of Computer Science, University of Helsinki
Helsinki, Finland
arto.klami@helsinki.fi

Ari Salmi
Electronics Research Lab., University of Helsinki
Helsinki, Finland
ari.salmi@helsinki.fi

Edward Hæggström
Electronics Research Lab., University of Helsinki
Helsinki, Finland
edward.haeggstrom@helsinki.fi

***Abstract* — Localizing fouling in industrial pipes by AI-enhanced ultrasonic means shows promising results. However, the existing methods require large quantities of data measured from multiple locations and thus are either costly due to the number of transducers required or are hampered by readout uncertainties due to reattachment of the sensors. We present a wireless and affordable network of custom-built clamp-on transducers with drive electronics, in which transducers can be used as both transmitters and receivers. The network was used to generate and characterize propagating waves in pipes with and without fouling. The transducers and their driving electronics generate signals with sufficient signal-to-noise ratio in a repeatable manner and are sensitive enough to detect the signal change caused by fouling on a steel pipe.**

Keywords—Transducer system, wireless sensor, fouling detection, industrial application, non-destructive testing

I. Introduction

Industrial equipment, such as pipelines and heat exchangers, accumulate fouling over time which reduces efficiency of the equipment and can cause permanent damage [1]. Consequently, non-destructive testing methods which use ultrasound to detect fouling in pipes have been developed [2]. Ultrasonic guided waves can propagate long distances along the pipes with little attenuation and are sensitive to the frequency-thickness product of the waveguide. Upon reaching defects, acoustic energy of the propagating wave is partially reflected and refracted [3] which alters the waveform measured by the receiving sensor.

There are two common methods to localize damage or fouling. One is based on the line-of-sight signal analysis between each pair of transducers [4], whereas the other is based on wave scattering off the defects [5]. Both methods employ multiple circumferential paths around the structure, enabling more extensive fouling localization due to greater coverage of the pipe surface by the signal paths [4-7]. Information revealed by the circumferential paths can effectively be utilized by artificial intelligence (AI) -based algorithms [8, 9], which benefit from large quantities of data measured from multiple locations.

For such localization tasks we employed low-cost transducers along with drive electronics to make fouling detection more economically efficient. To avoid readout uncertainties due to reattachment of the sensors, the transducers were designed to be permanently coupled to the structure under investigation. Moreover, each of the transducers can transmit and receive, thus providing richer circumferential information. Transducer communication with the host computer via wireless protocol avoids cabling issues. This configuration enables arbitrary sensor placement and facilitates the use of numerous sensor units, and hence constitutes a significant step towards making wide-ranging fouling detection possible for industrial use. A static installation could be used for continuous monitoring of pipe systems and the resulting high volumes of data boost development of AI methods by providing long-term data collections that cannot be obtained in laboratory setups.

II. Materials & Methods

A. Custom transducers

The transducer (Fig. 1) features a 3D printed PLA body (ø = 30 mm), a 370 kHz or 450 kHz piezoelectric disk (ø = 7 mm and 5 mm), and a glass sheet. The frequency responses of the transducers were measured using a vector network analyzer (HP 3589A) and an S-parameter test set (HP 35689A). This allows calibrating out individual differences between the transducers.

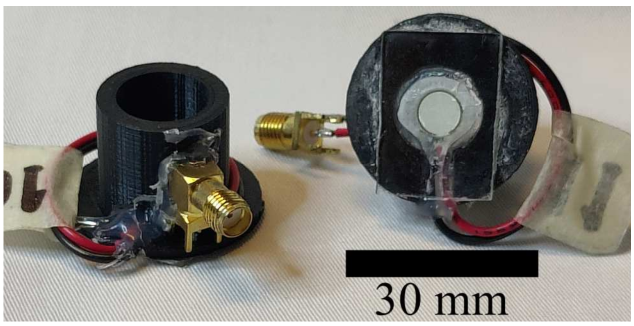

Fig. 1. Custom-made transducers consisting of PLA body, a piezoelectric disk, and a glass sheet.

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

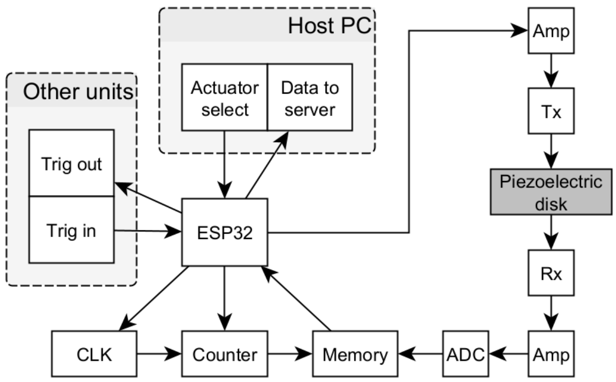

Fig. 2. Block diagram of sensor unit containing the drive electronics and a transducer.

B. Electronics

A sensor unit consists of a transducer and a control unit (Fig. 2). The control unit was built on a microcontroller module (ESP32-WROOM-32E) which communicates with a host computer and other identical units (Fig. 2). In transmit mode, the unit sends a trigger signal to other units and actuates the piezoelectric disk by charging and discharging it through a FET switch. A four cycle long 373 kHz square wave was used to actuate the piezoelectric disk. Upon receiving a trigger signal, the other units change to a listening mode in which the propagating wave is detected by the piezoelectric disk. The signal was sampled with a frequency of 4 MHz, then read to a memory chip and sent to the host computer via local wireless network. Total cost for the materials for one sensor unit is approximately 40 €, which can be lowered by bulk purchasing the components.

C. Sensor evaluation

To evaluate the basic functions of the sensor units, a two-sensor fouling detection test was conducted. Two 370 kHz transducers were coupled to a steel pipe (outer diameter 127 mm, wall thickness 2.0 mm) with ultrasound gel (Aquasonic 100) as shown in Fig. 3, with an 80 cm distance between. As a phantom for fouling, adhesive pads (HERMA Adhesive pads) (2.5 cm x 11.5 cm x 1.0 cm) were placed on the pipe lengthwise. A reference measurement was made on a clean pipe. Two fouling locations were tested, one on top of the pipe, directly between the transducers, and one on the opposite side on the bottom of the pipe. For each measurement set, 10 repeated measurements were made using a 25 V actuation voltage. The signals were processed afterwards with a 350-500 kHz bandpass filter to extract the dominant frequency range.

D. Fouling detection network

A typical use case for the sensor network is detection of fouling. To evaluate the solution in this context, we conducted a fouling detection test with multiple different fouling locations (Fig. 4). A network of five 450 kHz transducers was coupled to a steel pipe (outer diameter 154 mm, wall thickness 2.0 mm) with epoxy glue (CircuitWorks CW2400). A symmetric transducer placement was chosen for an even coverage of the pipe, allowing better comparison of signals between symmetric sensor and fouling configurations. The transducers were placed along the pipe with a separation of 30 cm for a total span of 120 cm, the middle transducer being the transmitter and the others being receivers. Transducer locations alternated between the top and bottom of the pipe. Adhesive pads (HERMA Adhesive pads) (5 cm x 5 cm x 0.6 cm) were used as a phantom for fouling. A reference measurement was made on a clean pipe. Four different fouling locations were tested, with fouling phantoms located directly between the transmitter and each of the receivers. For each measurement set, 10 repeated measurements were made using a 25 V actuation voltage. The signals were processed afterwards with a 350-550 kHz bandpass filter to extract the dominant frequency range.

III. Results & Discussion

A. Sensor evaluation

The acoustic wave generated by the transducer travels multiple times around the cylindrical geometry of the pipe, resulting in multiple wave packets detected by the receiving sensor. These wave packets travel through different paths determined by the number of cycles traveled around the pipe, ballistic path being the shortest path between the sensors followed by the circumferential paths. Due to the different propagation paths, certain wave packets can intersect with fouling, while others remain unaffected. This results in a

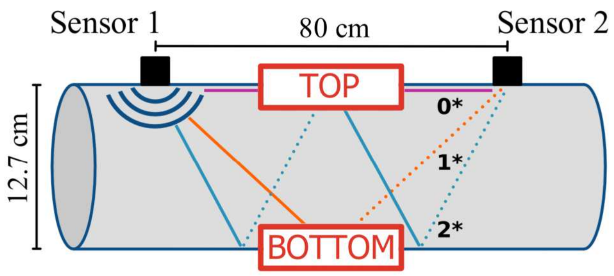

Fig. 3. Two-sensor measurement setup with 370 kHz transducers. The distance between the sensors was set to 80 cm. A reference signal was made on a clean pipe, and two measurements were made with fouling on top and bottom of the pipe. 0*: Ballistic path. 1*: 1st circumferential path. 2*: 2nd circumferential path.

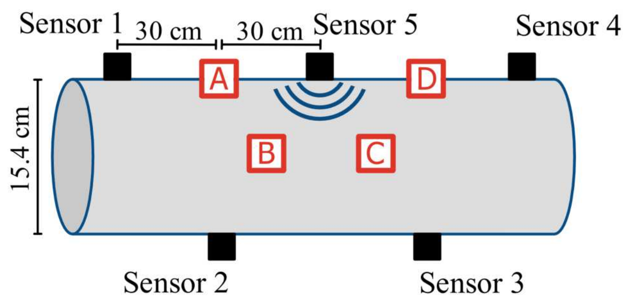

Fig. 4. Five-sensor network with 450 kHz transducers. Sensor 5 was transmitting and sensors 1-4 were receiving. Measurements were made on a clean pipe and four measurements were made with fouling in locations A-D.

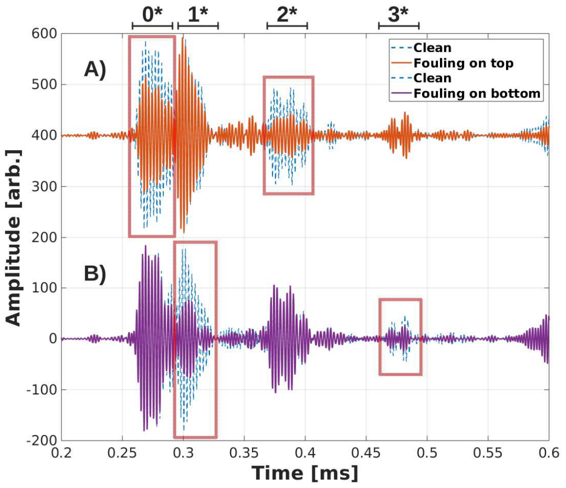

Fig. 5. Experimental results. Comparison of signals recorded with fouling present A) on top of the pipe, B) on bottom of the pipe. The averaged signals measured on the fouled pipe are overlaid on top of the signals from the clean pipe. n* marks the arrival time of n-th circumferential path. The red boxes highlight the paths that were expected to travel through fouling (Fig. 3).

decreased amplitude in the affected wave packets in comparison with a clean pipe signal.

Fig. 5 shows the averaged signals measured on the fouled pipe overlaid on the reference signals from the clean pipe. In Fig. 5A a fouling phantom is located on top of the pipe, and in Fig. 5B on the bottom of the pipe. A detectable decrease in signal amplitude compared to the reference signals is seen for even order circumferential paths in Fig. 5A and odd order circumferential paths in Fig. 5B, which agrees with geometrical consideration (Fig. 3). The change in amplitude is seen in wave packets on paths intersecting the fouling phantom. With fouling phantoms directly between the sensors, wave packets on the ballistic path and second circumferential path around the pipe have decreased amplitude compared to the clean reference signal. With fouling phantoms on the opposite side, the wave packets on the first and third circumferential paths exhibit a decreased amplitude. The experiment validates that the sensors are able to detect changes in signal waveform introduced by fouling, and are able to differentiate wave packets traveling on different paths.

B. Fouling detection network

The sensor network performed similarly to the two-sensor measurement setup but with more signal paths to monitor. Permanent coupling of the transducers using epoxy improved the signal-to-noise ratio compared to the previous experiment with ultrasound gel coupling.

Fig. 6 depicts the set of data from the network measurement (Fig. 4). The rows (1-4) denote the data collected by each transducer, while columns (Clean, A-D) correspond to different fouling configurations. To see the effect of the fouling, the envelopes of the averaged signals were extracted and the envelope of the clean reference was subtracted from the envelope of the fouled signals. The leftmost column (Clean) is a comparison of two measurements without a fouling phantom. The standard error for each signal maximum was on average 3.0 % of the amplitude.

Fig. 6 indicates that when a fouling phantom is located directly between the transmitting and receiving sensor, the magnitude of the difference in signal envelopes is the greatest. When the fouling phantom does not overlap with the circumferential trajectories, the signal envelopes are more akin to the clean reference. Furthermore, the changes seen in the waveforms are at similar times in symmetric transducer and fouling configurations. Comparing data measured by sensor 2 with fouling in location B (2B) to data at 3C, in both cases the two greatest features are seen around t = 0.15 ms and t = 0.25 ms. Similarly, data at 1A and 4D

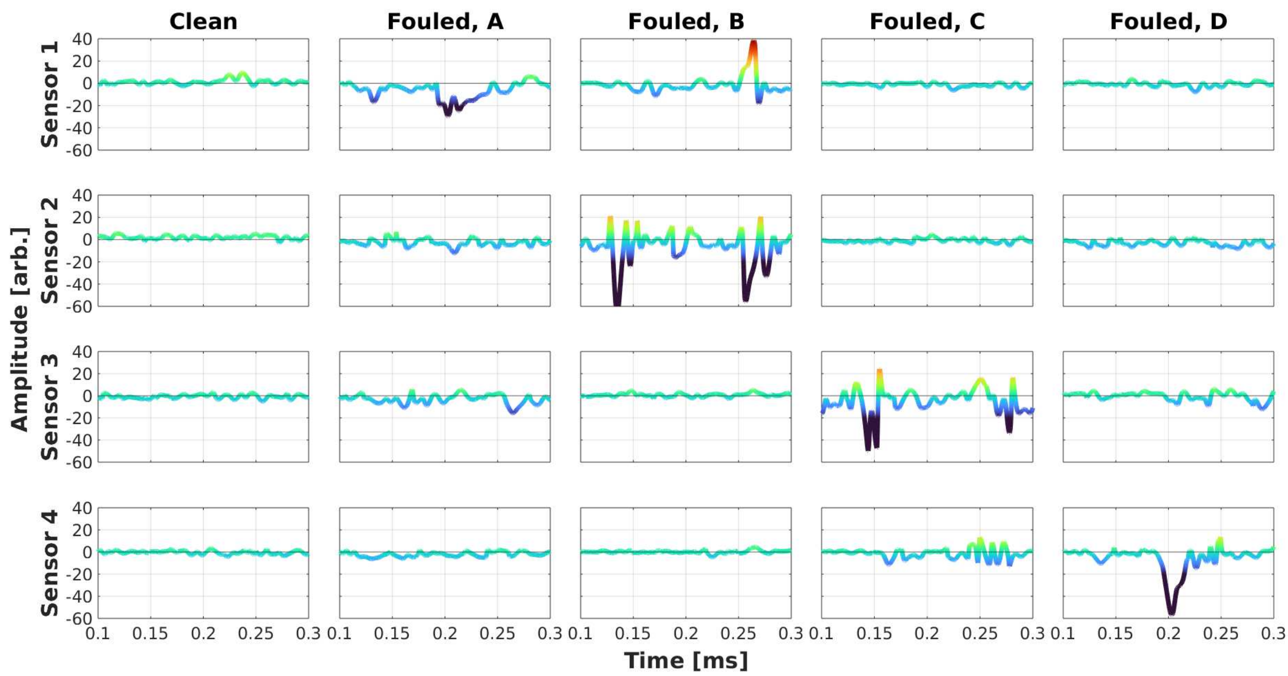

Fig. 6. Experimental results. Differences of averaged signal envelopes from a fouled and a clean pipe with respect to separate clean pipe measurement. Four different fouling locations (A-D) depicted in Fig. 4 were tested.

have the greatest features at t = 0.2 ms, although with differing amplitudes. These results validate that the sensor network can be used to reliably gather large quantities of data for AI-based fouling localization applications. If the wave packets are well-defined, more information on the different propagation paths can be obtained as the overlap of the signal features is reduced, thus fouling can be localized more accurately. The locations of the sensors could be optimized with AI-based methods to maximize the information content provided by the sensor network by following the principle outlined in [8].

IV. CONCLUSIONS

We showed a permanently attached, low-cost sensing network accurate enough to detect changes in signal waveforms caused by fouling, provided that a reference measurement of the clean pipe existed. The drive electronics generate and measure signals consistently with a standard error of 3.0 % in characteristic regions of the signals. Components for the sensor and control unit cost ~40 €. Closer examination of the waveforms in rows of Fig. 6 measured by the sensor network could provide hints about the location of the fouling.

ACKNOWLEDGMENT

The authors thank M.Sc. J. Mustonen (Electronics Research Lab., University of Helsinki) for his help in signal analysis.

REFERENCES

[1] J. MacAdam and S. A. Parsons, “Calcium carbonate scale formation and control,” Rev. Environ. Sci. Biotechnol., vol. 3, pp. 159-169, June 2004.

[2] K. R. Lohr and J. L. Rose, “Ultrasonic guided wave and acoustic impact methods for pipe fouling detection,” J. Food Eng., vol. 56, pp. 315-324, Mar. 2003.

[3] E. H. Ling and R. H. Abdul Rahim, “A review on ultrasonic guided wave technology,” Aust. J. Mech. Eng., vol. 18, pp. 32-44, Nov. 2017.

[4] E. Dehghan-Niri and S. Salamone, ”A multi-helical ultrasonic imaging approach for the structural health monitoring of cylindrical structures,” Struct. Hlth. Monit., vol. 14, no. 1, pp. 73-85, Jan. 2015.

[5] A. Golato, F. Ahmad, S. Santhanam, and M. G. Amin, “Multi-helical path exploitation in sparsity-based guided-wave imaging of defects in pipes,” J. Nondestruct. Eval., vol. 37, no. 2, p. 27, Mar. 2018.

[6] P. Huthwaite and M. Seher, “Robust helical path separation for thickness mapping of pipes by Guided Wave Tomography”, IEEE T. Ultrason. Ferr., vol. 62, no. 5, pp. 927-938, May 2015.

[7] C. L. Willey, F. Simonetti, P. B. Nagy, and G. Instanes, ”Guided wave tomography of pipes with high-order helical modes,” NDT&E Int., vol. 65, pp. 8-21, July 2014.

[8] K. Longi, C. Rajani, T. Sillanpää, J. Mäkinen, T. Rauhala, A. Salmi, E. Hæggström, and A. Klami, ”Sensor placement for spatial gaussian processes with integral observations,” PMLR, Aug. 2020, pp. 1009-1018. [Proceedings of the 36th Conference on Uncertainty in Artificial Intelligence (UAI)]

[9] T. Sillanpää, T, Rauhala, J. Mäkinen, C. Rajani, K. Longi, A. Klami, A. Salmi, and E. Hæggström, ”Ultrasonic fouling detector powered by machine learning”, 2019 IEEE Int. Ultra. Sym., 2019.