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SENSORDEVICES 2010:

The First International Conference
on Sensor Device Technologies and Applications

July 18 - 25, 2010 - Venice, Italy



The inaugural event SENSORDEVICES 2010, The First International Conference on Sensor Device Technologies and Applications, initiates a series of events focusing on sensor devices themselves, the technology-capturing style of sensors, special technologies, signal control and interfaces, and particularly sensors-oriented applications. The evolution of the nano- and microtechnologies, nanomaterials, and the new business services make the sensor device industry and research on sensor-themselves very challenging.

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Sensor devices
Sensor device technologies
Sensors signal conditioning and interfacing circuits

Medical devices and sensors applications
Sensors domain-oriented devices, technologies, and applications
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Registration: April 15, 2010
Camera ready: April 20, 2010



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SENSORCOMM 2010:

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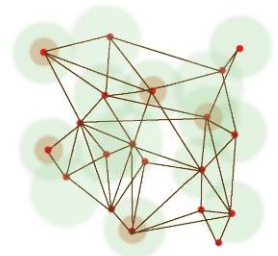
SENSORCOMM 2010 (The Fourth International Conference on Sensor Technologies and Applications) is a multi-track event covering related topics on theory and practice on wired and wireless sensors and sensor networks. The topics suggested can be discussed in term of concepts, state of the art, research, standards, implementations, running experiments, applications, and industrial case studies.

Conference tracks

APASN Architectures, protocols and algorithms of sensor networks
MECSN Energy, management and control of sensor networks
RASQOFT Resource allocation, services, QoS and fault tolerance in sensor networks
PESMOSN Performance, simulation and modelling of sensor networks
SEMOSN Security and monitoring of sensor networks
SECSN Sensor circuits and sensor devices
RIWISN Radio issues in wireless sensor networks
SAPSN Software, applications and programming of sensor networks
DAIPSN Data allocation and information in sensor networks
DISN Deployments and implementations of sensor networks
UNWAT Under water sensors and systems
ENOPT Energy optimization in wireless sensor networks

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Vibration Analysis Based on Hammer Impact for Fouling Detection Using Microphone and Accelerometer as Sensors

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Abstract: The easy detection of fouling in duct systems is a persistent problem and remains a relevant demand for the chemical, oil, food and pharmaceutical industries. The fouling process is the slow, unwanted layer deposition of heavy organic and other dissolved solid materials out of transported fluids or suspensions onto inner wall surfaces in fluid transport systems over an extended period of time. This work presents research results of vibrational hammer excitation for easy to use external non-invasive, non-destructive fouling detection in pipelines and other large scale duct systems. The main goal is the detection of inner pipe layer formation, and thickness estimation of the adsorbed material. Data were taken from the vibration amplitude variation in presence of an inner pipe fouling layer using acoustic accelerometer and microphone detection. The experimental set-up and achievable sensitivities and of the methods are outlined. *Copyright © 2010 IFSA.*

Keywords: Acoustic vibrations analysis, Hammer impact test and fouling detection

1. Introduction

A severe problem which occurs for fluid transport in duct systems and pipelines is the slow accumulation of organic or inorganic substances in their internal surfaces with time. Such accumulation of unwanted material is denoted fouling, and occasionally appears simultaneously with tube corrosion. Both, fouling and corrosion are major concerns for plant operation and life time in the chemical, petroleum, food and pharmaceutical industries, due to their detrimental impact on reliability and security [1-2]. Tube corrosion is related to the presence of chemically aggressive trace elements and compounds in the transported materials, usually attributed to presence of sulfur or halogens. Sulfur typically transforms in presence of water into sulfuric acid, which attacks the wall metal, thus reducing

wall thickness. Appropriate selection of high quality steels for the tube material and / or cathodic polarization protection reduces the risks for tube corrosion.

Duct systems and pipelines thus require regular, periodic inspection. Several methods have been proposed for early fouling detection in ducts, based on mass flow reduction, electric resistance and eddy current sensors and ultrasonic techniques [3-6]. Some works are related with fouling detection in food industry [23-25]. Tests with hammer impact have been used before in numerous engineering areas to analyze frequency response functions (FRF), due to convenience and simplicity of the experiments, as well as the validity of the analysis procedures [7-9]. The physical principle is simple, and well known as the ringing bell: when the tube is mechanically excited by hammer impact, a relatively localized area of the tube section begins to vibrate at acoustic frequencies for a certain period of time at one or more resonance frequencies. The vibration propagates as very fast shear sound wave within the duct wall, and as a surface wave. The latter couples to the environmental air and is acoustically detectable by a closely mounted microphone. As confirmed by finite element (FE) calculations at sufficiently low load levels, the mechanical hammer impact onto the duct surface also causes an elastic surface deformation wave, which propagates at lower speed across the surface. It can be monitored by an appropriately designed accelerometer, firmly attached onto the surface near the impact point. Due to internal damping, the hammer excited vibration attenuates rapidly. The temporal development and decay of the free vibration depends on the physical characteristics of the system / pipe geometry, especially of the damping coefficient [7], which is determined by the wall thickness.

Flaw detection in mechanical structures based on vibration methods have been reported earlier [10-12]. Some of these techniques compare recorded resonance frequencies with those obtained from a finite element analysis [10, 11]. Mechanical vibration tests have been implemented and used for flaw detection in structures [7-12]. The detection of cracks in beam structures has been reported before in Refs. [13-18] while flaw detection in antique artworks has been investigated in Refs. [19-20]. Ewins et. al. [26-28] presents works related with modal analysis.

Based on ideas presented earlier, the acoustic hammer excitation / impact has been evaluated in this work towards simplified fouling detection in ducts and pipelines, used for crude oil transport and plant processing. Here, we analyze variations in vibration amplitude, frequency and decay / attenuation time using microphone and accelerometer output signals in presence of inner tube fouling layers. The main contribution of this work is the use of an easy to implement method for fouling detection, which uses a non-invasive technique, with the hammer test.

The asphaltic fouling layer that was originally deposited in crude oil ducts has been replaced and simulated by a paraffin (resin) film with a defined and varying thickness up to 15 mm that has been carefully deposited within the test tube.

2. Vibration Method

In this work, a fouling detector has been exploited, using the hammer test to provoke mechanical vibrations in the pipe section under investigation. The acoustic detection system comprises either an accelerometer or a microphone to capture the acoustic signatures of the tube vibrations. Fig. 1 (a) represents a sketch of the experimental set-up using a microphone as detector and Fig. 1 (b) shows the experimental set-up using an accelerometer as detector. The impact points in each test have been maintained to assure the same test conditions in each experiment and the pipes are supported by two fixed supports in the extremity of the tubes. An electromagnetic displacement system has been installed to establish controlled and reproducible hammer movements and force / momentum transfer, for localized vibration excitation in the pipe section under test. Both, a commercial MEMS accelerometer sensor from Analog Devices type ADXL 202 and a high quality microphone from

Sennheiser type Cardioid GM 580 (Bandwidth: 50 Hz to 13 kHz) have been employed for the investigations. The MEMS detector has been glued onto the tube circumference at a distance of 2 cm (l_1) from the hammer impact point. The microphone has been mounted at the same distance, but without mechanical contact to the test tube. A detailed description of the set-up is provided in Silva [21-22].

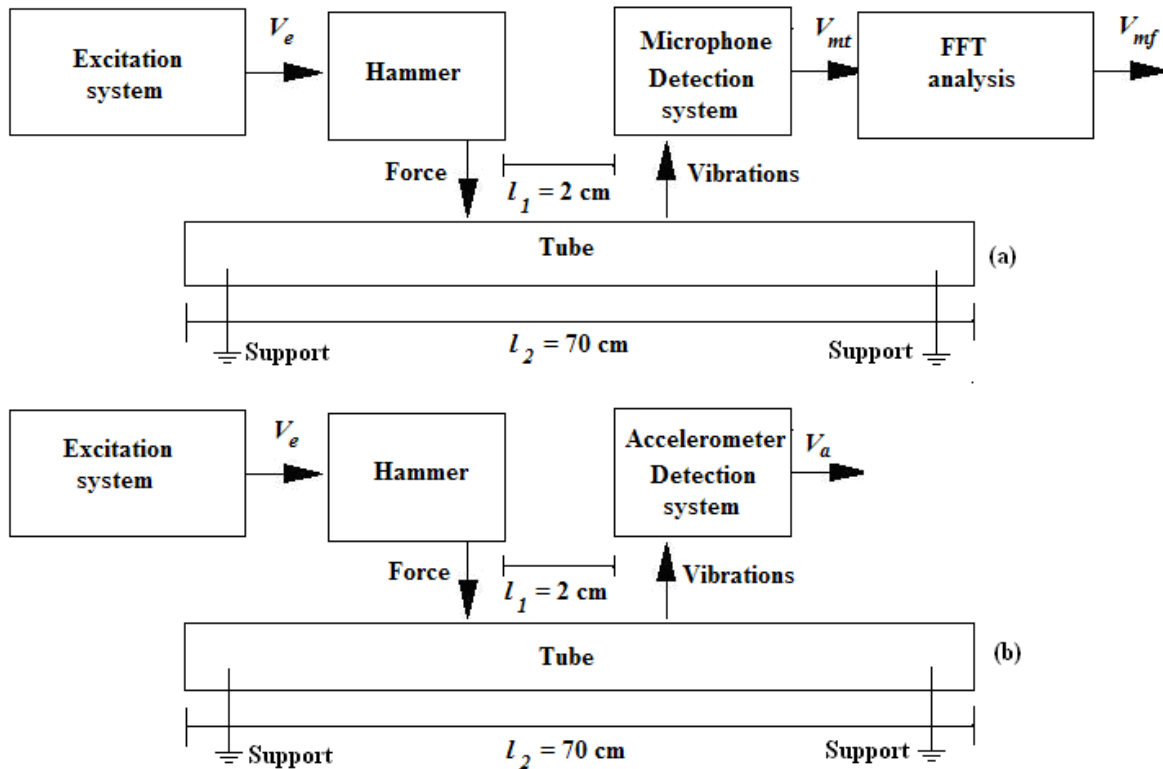


Fig. 1. Sketch of the experimental set-up with: (a) microphone and (b) accelerometer.

The electromagnetic displacement system is formed by a DC power supply and for a pulse generator, that excites a coil and it activate the hammer, making the hammer to hit the pipe. The hammer excitement signal frequency is controlled for the pulse generator. The sample rate of the data acquisition is 200 MHz and the force impact has a repeatability of 2 Hz, this frequency is used to control the repeatability of the hammer impact onto the tube. The applied force onto surface of the test tube was 0.4 N, as determined by a digital dynamometer, well maintaining the impact load magnitude. We observe, with experimental tests, that 4 averages are sufficient to reject ambient noise.

To reduce interference with background noise, the microphone and accelerometer have been localized close to the hammer impact. In case of the presence of inhomogeneous fouling layers; the method would provide an averaged value, taken over the localization accuracy. This quantity has been determined to 6-9 cm for the model geometry. Non-axisymmetric fouling distributions have not been explored in this work, but will be included and part of an extended future analysis.

Quantitative data, regarding the thickness of the fouling layer, were extracted from the acoustic power attenuation characteristics, the shift of the resonance frequencies, and the signal decay time as a function of film thickness. From all sensor arrangements, detector sensitivities were estimated. The accelerometer was biased by a constant current source, and the signal fed into an instrumentation amplifier, followed by a digital oscilloscope (Agilent model 54622A) and a HP spectrum analyzer was used to observe the microphone signal output. The ADXL202E is a low-cost, low-power, 2-axis

MEMS accelerometer with a digital output, integrated onto a single monolithic IC. Both quantities are recorded, dynamic acceleration (e.g. the vibration) and static force (e.g. gravity or tilt angle). The outputs are analog voltage or digital signals, whose duty cycles (ratio of pulse width to period) are proportional to acceleration.

3. Methodology used in the Tests

The used methodology consists of the observation in parameter variations, amplitude and frequency, in the monitored signals, using the detection system with the accelerometer and microphone [21-22].

3.1. Tests with the Accelerometer

A sketch of the accelerometer output signal is presented in Fig. 2. We can define the following expression for the maximum amplitude of the signal $V_a(t)$:

$$A = \max(V_a(t)), \text{ for } t \in [t_0, t_0 + iT], \quad (1)$$

where: $V_a(t)$ is the output signal of the detection system using the accelerometer and A is the maximum amplitude of the signal $V_a(t)$.

The mean value (A_m) for the maximum amplitude of the signal $V_a(t)$ is:

$$A_m = \frac{1}{N} \sum_{i=1}^N A_i(e), \quad (2)$$

where: N is the number of tests used in each experiment.

The increase in the fouling thickness (e) provokes a reduction in the amplitude maximum value in the output signal (A) and a reduction in the duration time of the signal (τ), in the tests with the accelerometer.

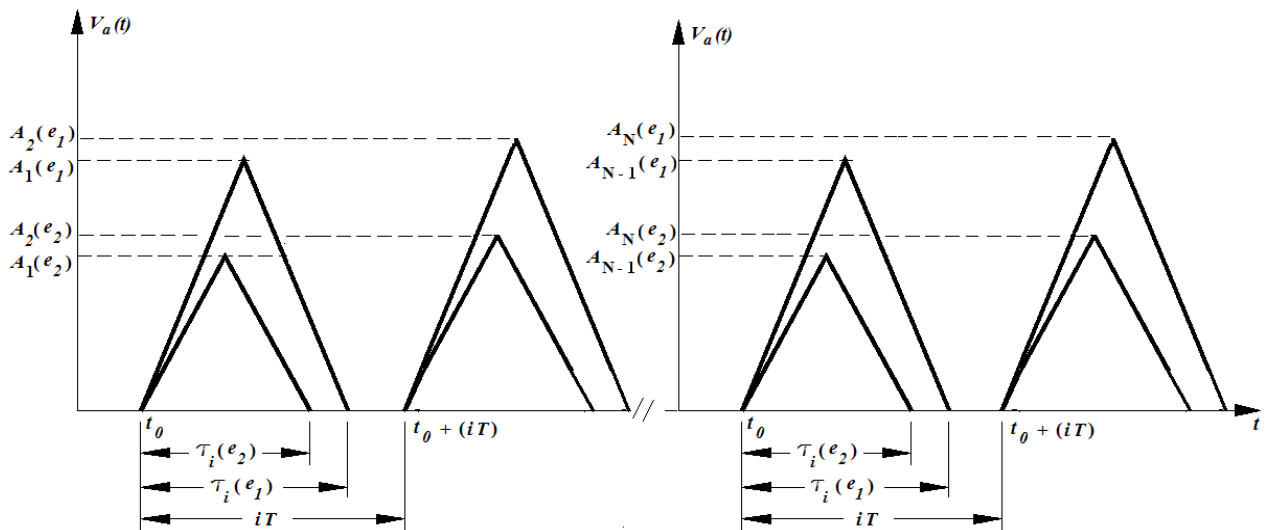


Fig. 2. Representation of the signal in the accelerometer output.

3.2. Tests with the Microphone in Time Domain

A sketch of the attenuated microphone output signal in the time domain is presented in Fig. 3. We can define the following expression for the envelope of the signal $V_{mt}(t)$:

$$P(t) = P_0(1 - e^{-\frac{t}{d}}), \quad (3)$$

where: $V_{mt}(t)$ is the output signal of the detection system using the microphone, in time domain, $P(t)$ is the envelope signal and $d = t$ is the decay time of the signal $V_{mt}(t)$, in other words, the necessary time to reduce the maximum amplitude (P_0) of the signal $V_{mt}(t)$ for 37 % of its value ($(1 - e^{-1}) P_0$).

The mean value (D_m) for the decay time of the signal $V_{mt}(t)$ is:

$$D_m = \frac{1}{N} \sum_{i=1}^N d_i(e) \quad (4)$$

where: N is the number of tests used in each experiment.

The increase in the fouling thickness (e) provokes a reduction in the value of the decay time (d) of the signal $V_{mt}(t)$ and a reduction in the maximum amplitude (P_0) of this signal, in the tests with microphone, in time domain.

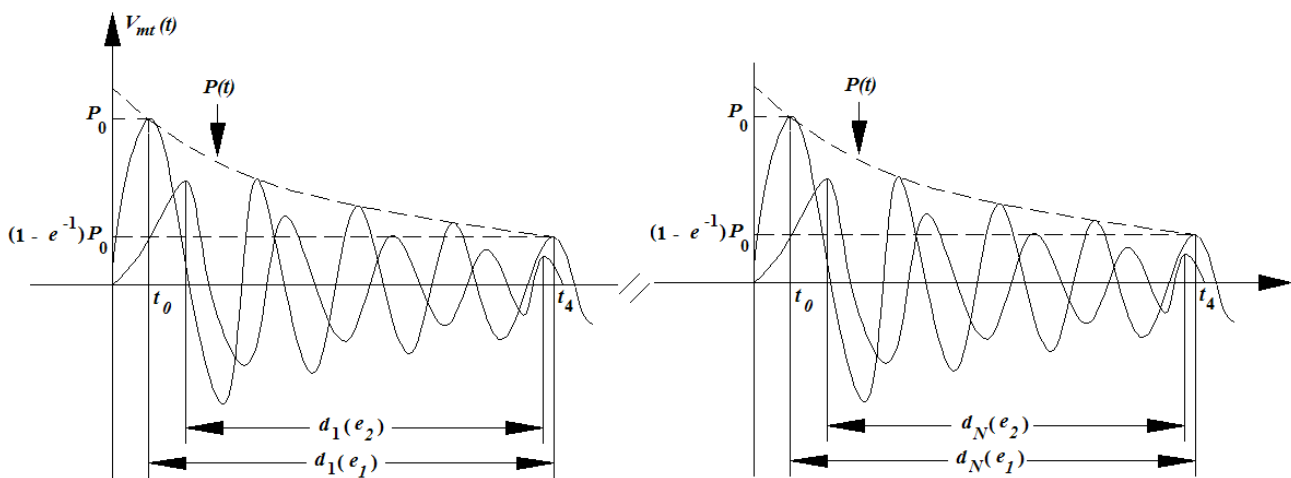


Fig. 3. Representation of the signal in the microphone output, in time domain.

3.3. Tests with the Microphone in Frequency Domain

A sketch of the attenuated microphone output signal in the frequency domain is presented in Fig. 4. We can define the following expression for the resonance frequency of the signal $V_{mf}(f)$:

$$f_{res} = \arg \max V_{mf}(f), \text{ for } f \in [f_0, f_1] \quad (5)$$

where: $V_{mf}(f)$ is the output signal of the detection system using the microphone, in frequency domain, and f_{res} is the resonance frequency of the signal $V_{mf}(f)$, in other words, the frequency (f) where occur the maximum value (V) of the signal $V_{mf}(f)$.

The mean value (F_m) for the resonance frequency of the signal $V_{mf}(f)$ is:

$$F_m = \frac{1}{N} \sum_{i=1}^N f_{resi}(e), \quad (6)$$

where: N is the number of tests used in each experiment.

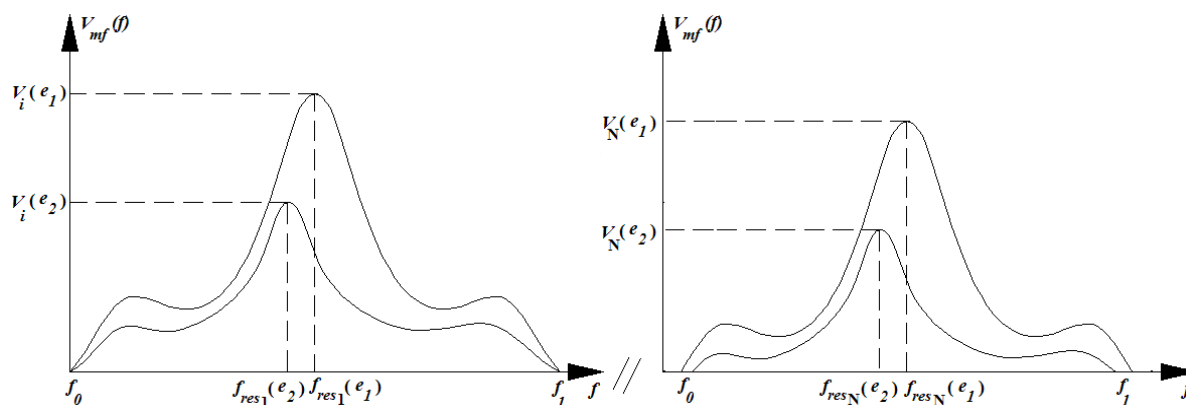


Fig. 4. Representation of the signal in the microphone output, in frequency domain.

The increase in the fouling thickness (e) provokes a reduction in the value of the resonance frequency (f_{res}) of the signal $V_{mf}(f)$ and a reduction in the maximum amplitude (V) of this signal, in the tests with microphone, in frequency domain.

4. Experimental Results

A calibration step to define the original acoustic tube signature is initially accomplished in absence of a fouling layer. The received signal is monitored, and the acoustic features (amplitude, frequency) stored as reference. The test tube comprises a wall thickness of 2.5 mm (w), a diameter of 10 cm (R), a length of 0.7 m (l_2), made from galvanized iron as illustrated in Fig. 5.

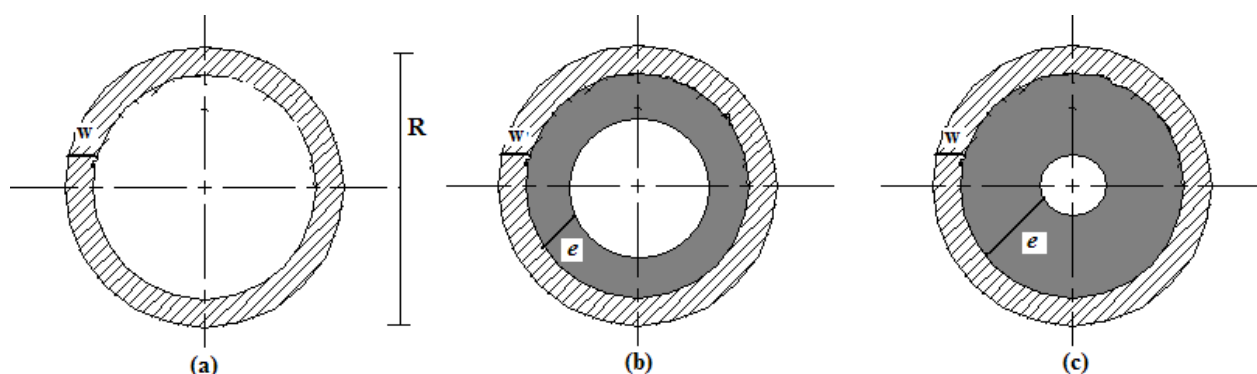
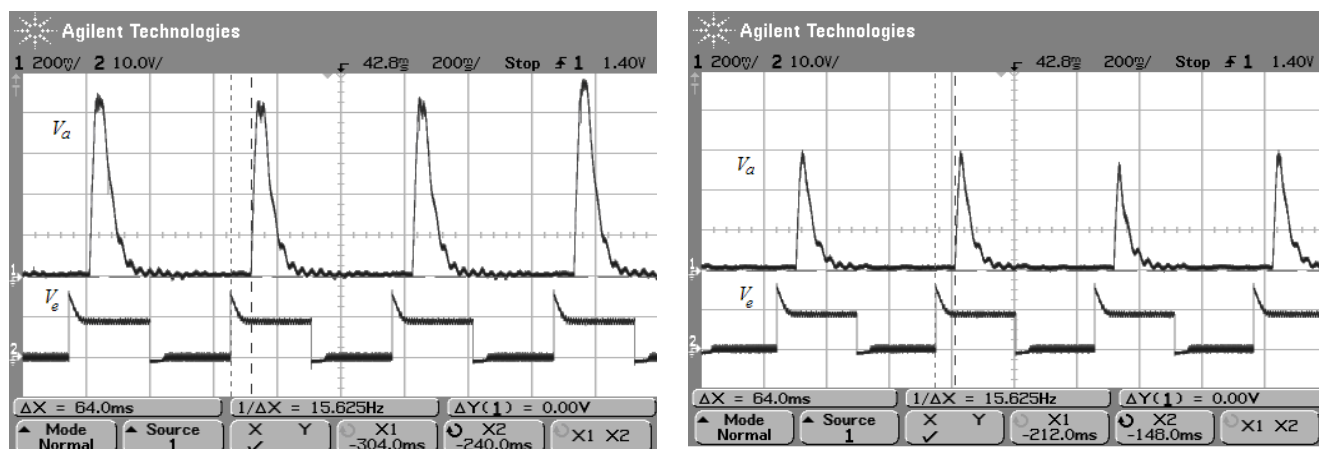


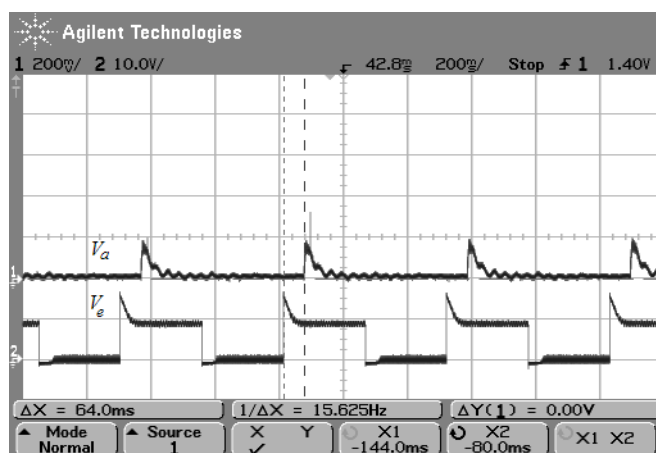
Fig. 5. Traverse view of the tubes: (a) without fouling; (b) with 5 mm of fouling, and (c) with 15 mm of fouling (resin).

The temporal evolution of the applied hammer impact force load (V_e), recorded by the accelerometer, is illustrated in the lower trace of Figs. 6a-c. Using a feedback-loop circuit, the signal is used to stabilize the impact frequency and magnitude.



(a) In absence of fouling.

(b) For 5 mm fouling thickness.



(c) For 15 mm fouling thickness.

Fig. 6. Accelerometer output signals (V_a) and excitation signal (V_e): in absence of fouling (a), for 5 mm fouling thickness (b) and 15 mm fouling thickness (c).

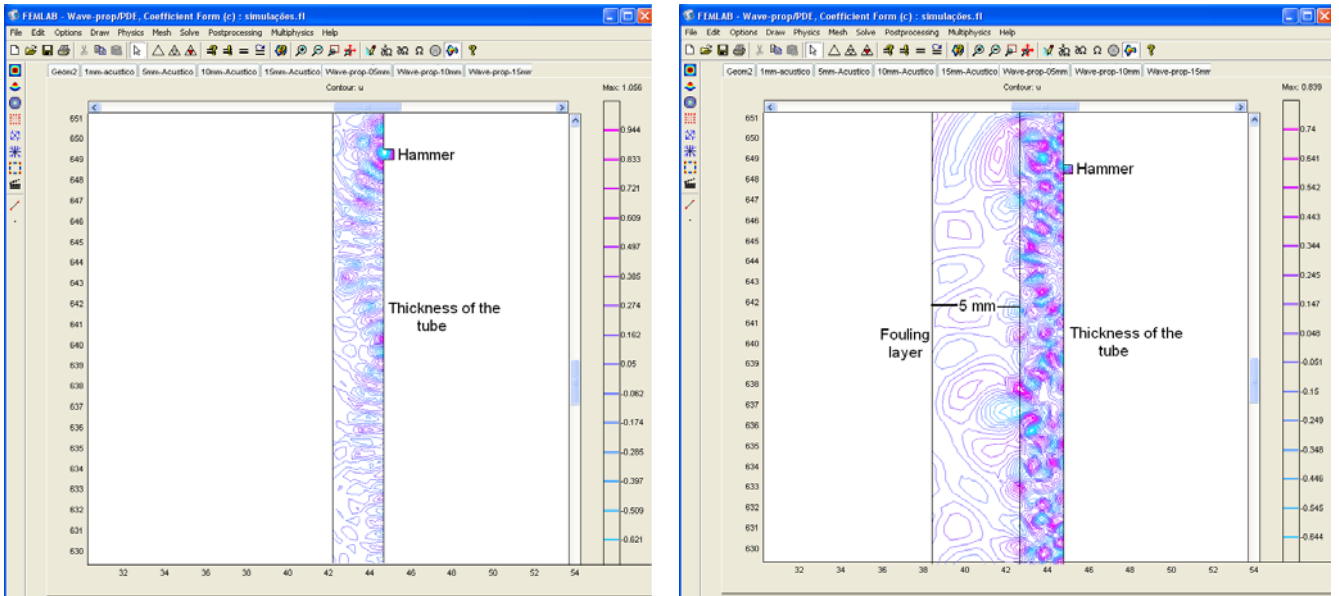
4.1. Obtained Results with Accelerometer

The monitored and stored accelerometer output signals (V_a) are illustrated in the upper traces of Figs. 6 (a-c) in absence of fouling, and for fouling layer thickness of 5 and 15 mm, respectively. The time delay and propagation time between force impact and detection at the accelerometer is 64 ms, and does not vary with the fouling layer thickness. Typically, the accelerometer response signal (V_a) features a sharp spike. The signal obtained in the detector output, using the accelerometer, corresponds to the equivalent peak value of the impact generated by the hammer. The circuit of the detector captures the equivalent peak value of the vibration in the y axis of the accelerometer. With increasing film thickness both, the overall signal magnitude and width are decreasing. Persistent low magnitude ringing, observable in all time signals, most likely originates from a resonance in the MEMS accelerometer itself, where its spring type cantilever design supports the oscillating response

characteristic. The typical value for the number of waveform used in each experiment (N) is 4 and the data are obtained with 200,000 points.

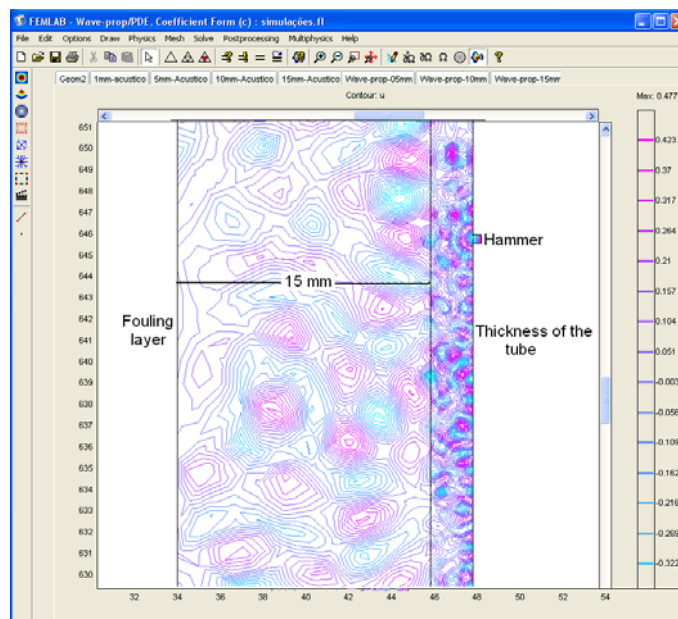
4.2. Obtained Results with Finite Elements (FE)

Simulations using the software FEMLAB, for analysis of finite elements, were carried out to support the experimental results, obtained with the accelerometer. The simulation results, using the hammer impact for the clean tube (a), with 5 mm (b) and 15 mm of fouling (c) are presented in Fig. 7.



(a) In absence of fouling.

(b) For 5 mm fouling thickness.

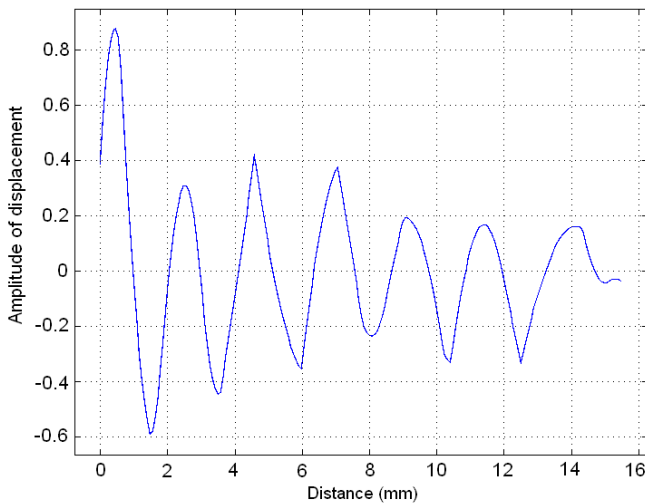


(c) For 15 mm fouling thickness.

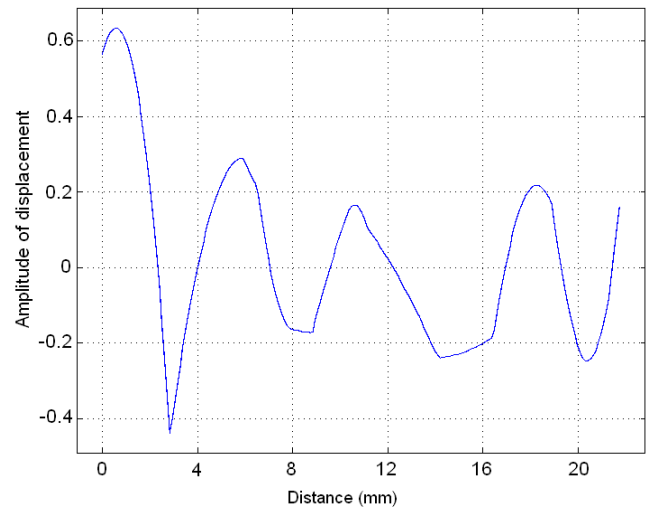
Fig. 7. Simulation without fouling (a), with 5 mm of fouling (b) and with 15 mm of fouling (c).

We observe that the signal (resulting from mechanical displacements) spreads into the new resin material, inside the tube, in accord with the presented contour curves. The tests were implemented with simulations using the same dimensions and characteristics of the tubes (galvanized iron) and the same thickness and characteristics of the resin [22]. The damping model is not included in the model. The density of the iron is 7.8 g/cm^3 and the density of the resin is 0.9 g/cm^3 , then the relative density is 8.7 and the elastic modulus of the iron is $2.0 \times 10^5 \text{ MPa}$, for the resin it is 200 MPa . Fig. 7 shows the contour curves of the spread signal in the tube, at a particular time-step. When the spread signal finds a new interface, different of the iron, there is a leakage in this interface (resin) as shown in these figures.

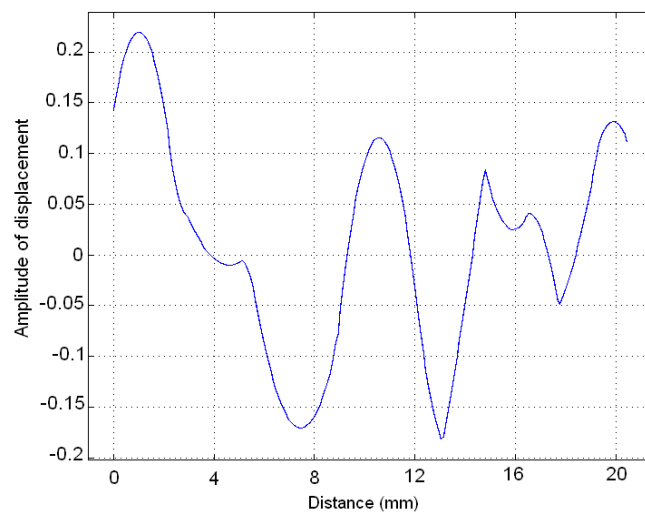
Using the software FEMLAB, spreading of mechanical displacements (deformation) begins at the hammer impact towards the accelerometer location, as shown in Fig. 8 for the clean tube (a), with 5 mm (b) and 15 mm of fouling (c). Fig. 8 represents a snapshot in time, with displacement plotted along a line and the three plots correspond to the same time relative to the hammer impact time. It is evident that the increasing fouling layer accounts for a reduction in the amplitude, thus confirming the experimental tests results.



(a) In absence of fouling.



(b) For 5 mm fouling thickness.

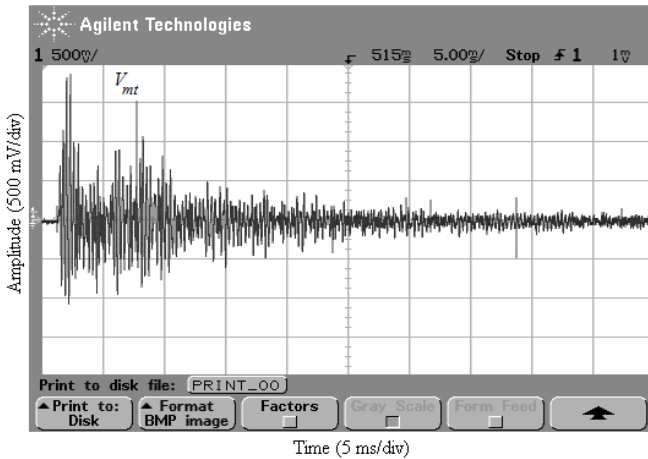


(c) For 15 mm fouling thickness.

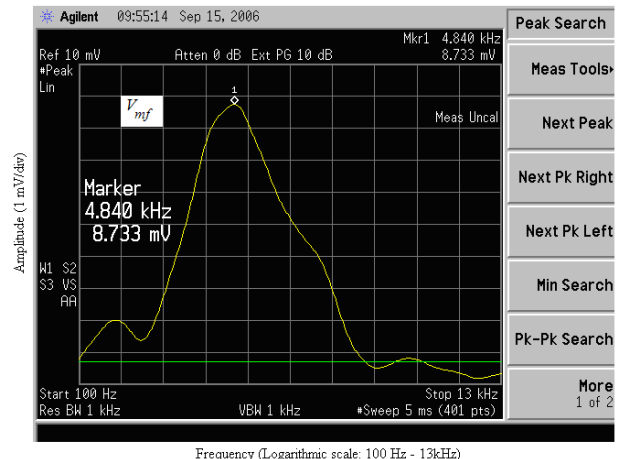
Fig. 8. Displacements graphics in tubes without fouling (a), with 5 mm of fouling (b) and with 15 mm of fouling (c).

4.3. Obtained Results with Microphone

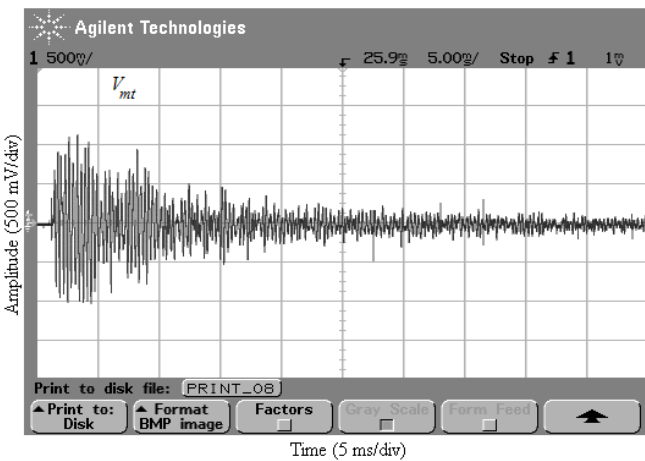
Microphone recordings of the acoustic signatures in the time domain (V_{mt}) are shown in Figs. 9 a-c. Fig. 9a reveals the signature of a clean test tube. Figs. 9 b and 9 c display the waveforms exhibiting a fouling layer thickness of 5 and 15 mm, respectively. Data were obtained without keeping liquid (water) in the tube. Figs. 9 (d-f) display the corresponding Fourier Transformed (FT) signal in the frequency domain (V_{mf}).



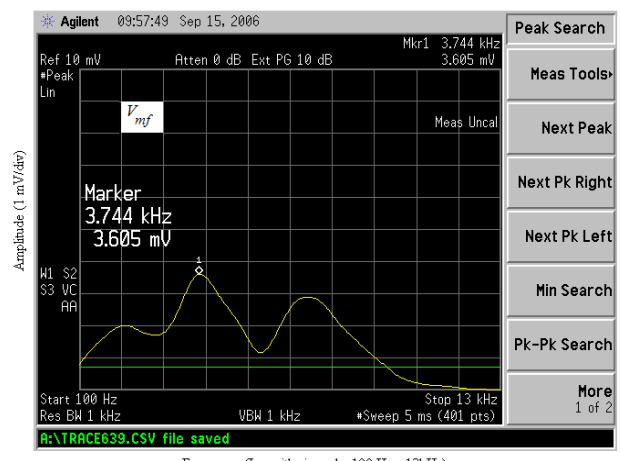
(a) Clean test tube.



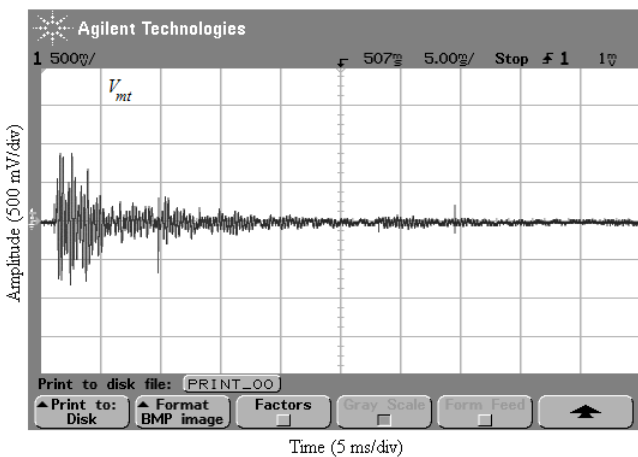
(d) FT data (clean test tube).



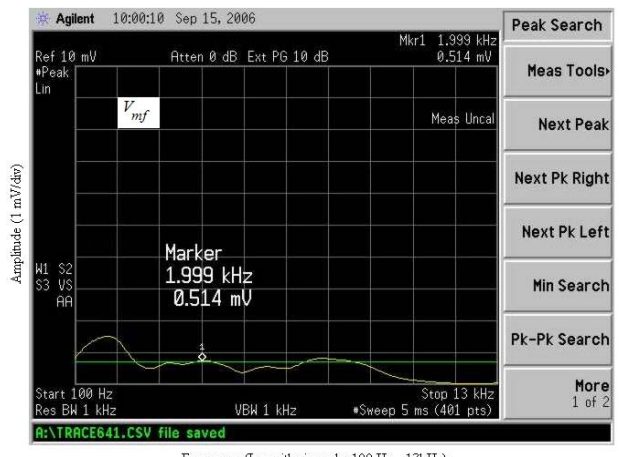
(b) Fouling layer thickness 5 mm.



(e) FT data (with 5 mm of fouling).



(c) Fouling layer thickness 15 mm.



(f) FT data (with 15 mm of fouling).

Fig. 9. Acoustic response in time domain V_{mt} (a, b, c) and frequency domain V_{mf} (d, e, f) in absence of fouling and for 5 and 15 mm thick fouling layers.

The acoustic sound / vibration signature for the fouling free case of Fig. 9 a decays approximately exponential over a time period of around 25 ms. The $(1/e)$ decay time period is approximately 14.1 ms. It decreases to 10.2 ms and 2.9 ms for fouling layer thickness of 5 and 15 mm, respectively. These values are determined graphically observing the necessary time to reduce the maximum amplitude of the signal $V_{mt}(t)$ for 37% of its value. The frequency spectrum of the clean tube, Fig. 9 d, reveals 3 vibrations modes at 1.1 kHz, 4.84 kHz (8.733 mV), and 7.15 kHz. The frequency of the second mode down shifts to 3.74 kHz (3.606 mV) for the 5 mm thick fouling layer (Fig. 9 e), while the first and third modes present small modifications. For the 15 mm fouling layer (Fig. 9 f), the frequency of the second mode down shifts to 1.99 kHz (0.514 mV) showing a somewhat reduced sensing range. The fouling layer has an effect on the natural frequencies of modes 1 and 3, but the mode 2 presents more notable reduction. The reason still is not fully clear to us. The typical values for the number of tests used in each experiment (N) are 4 measurements [21].

4.4. Sensitivity Criterion

Evaluation of the different sensing techniques for their achievable sensitivity criterion $S(\cdot)$, defined as the variation of the respective output signals (Δ) with the fouling layer thickness variation (Δe), and based on results displayed in Figs. 6 and 9 are illustrated in Figs. 10a-c.

The sensitivity criterion for the respective output signals are defined by:

$$(a) S(A) = \frac{\Delta A}{\Delta e}, \quad (7)$$

where ΔA is the variation of A and Δe is the fouling layer thickness variation.

$$(b) S(D) = \frac{\Delta D}{\Delta e}, \quad (8)$$

where ΔD is the variation of D and Δe is the fouling layer thickness variation.

$$(c) S(F) = \frac{\Delta F}{\Delta e}, \quad (9)$$

where ΔF is the variation of F and Δe is the fouling layer thickness variation.

From the experimental findings for the different sensing approaches, the following linearized figures of merit for fouling detection can be extracted:

(a) Using an accelerometers to quantify the magnitude of the elastic surface wave, the associated sensor, the sensitivity is determined to be $S(A) = -48,5$ mV/mm. Taking into account the sensor noise figure of 2.5 microvolt, the detectivity (or signal to noise ratio) determines to 19400. The available linear dynamic range is extrapolated to about a film thickness of 20 mm.

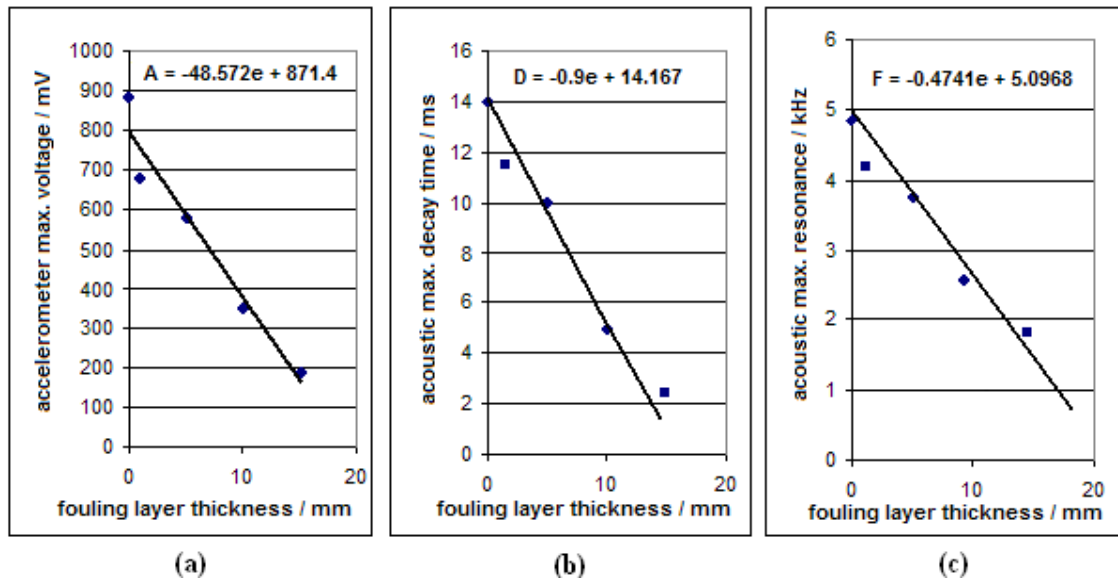


Fig. 10. Sensor output signals as function of fouling layer thickness (e); for the accelerometer (a); and acoustic microphone signatures (b) and (c).

(b) For microphone detection of the original acoustic signal decay in the time domain, the achievable sensitivity was estimated to be $S(D) = -0.9$ ms/mm. Taking into account the associated limited accuracy of approx. 0.1 ms, due to the high signal fluctuation level, the signal to noise ratio reduces to approx. 10. The available linear dynamic range extrapolates to about a film thickness of 15 mm.

(c) Employing the processed microphone signal in the frequency domain, upon performing a Fourier transformation, the achievable sensitivity is estimated to be $S(F) = -0.47$ kHz/mm. Assuming a spectral resolution of 1 Hz, the signal to noise ratio determines to 370. The available linear dynamic range also reduces to about a film thickness of 15 mm.

The observed dominating resonance sensitively depends on the tube geometry under consideration. For larger tube diameters, the tube vibration would shift to a lower dominating resonance frequency, while for thinner wall thickness an increase would be observed. Also, position and magnitude of the side bands would change. Supporting experiments have been carried out on a massive duct section, originally mounted in an oil processing plant. The tube was made of carbon steel, with length of 2 m, wall thickness approx. 1 cm, and diameter of 22 cm.

When the signal finds a new interface, different of the iron, there is a leakage in this interface (resin). For larger tube diameters with larger wall thickness, the tube vibration would shift to a lower dominating resonance frequency, due to the increased vibrating mass. For smaller diameter and thinner wall thickness, an increase would be observed, as experimentally verified.

Regarding microphone detection, although being technically much easier to implement, neither use of the directly obtained acoustic response decay in the time domain, nor Fourier transformed frequency readings would provide sufficient resolution for an autonomously operating sensor system, directly attached to a tube under consideration. However, based on our findings, for an experienced and well trained human operator, the presence of fouling can be detected manually by acoustic physiological listening to the hammer response, where frequency shifts in the audio region are relative easy to identify.

Accelerometer based autonomous fouling detection systems are relatively easy to design and should be preferably implemented at pre-determined duct sections, which are otherwise difficult to access, or exhibit an increased probability for the appearance of fouling. Changes in the response signal can be monitored automatically and continuously, and alarms provided, as soon as critical thickness levels are reached.

5. Conclusions

Tests with hammer impact have been used before in numerous engineering areas to analyze frequency response functions (FRF), due to convenience and simplicity of the experiments, as well as the validity of the analysis procedures. When the system is mechanically excited by hammer impact, the system / pipe vibrates for a certain period of time. Due to internal damping, the vibration decays rapidly. In fact, the duration time of the free vibration depends on the physical characteristics of the system / pipe geometry, especially of the damping coefficient.

In this work, a hammer impact test has been employed for fouling detection via vibration tube signatures. This method relies on vibration amplitude and frequency determination using an accelerometer and a microphone. It presents a practically usable non-destructive monitoring approach. Variations of amplitude and frequency signatures, resulting from the presence of inner tube fouling layers are easily observed. Absolute values of the output signal can be compared and modifications, as reduction, are clear indications for presence of fouling. Thus, the vibration amplitude and frequency reduction provides important information on the amount of tube fouling.

The hammer impact points in each test have been maintained to assure the same test conditions. The main advantage of the method is the simplicity of the measurements and determination of the parameters; a more sophisticated parameter estimation method was not required, once the values have been determined.

The microphone records the acoustic tube signature, due to excitation and propagation of a longitudinal wave, as known from the ringing bell. The origin of the signature recorded by the accelerometer is more difficult. We attribute it primarily to the transversal deformation wave, which propagates along the tube surface, similar to spreading of a surface water wave. This explanation is supported by our simulation, where the hammer impact causes spatially distributed surface deformations.

Acknowledgements

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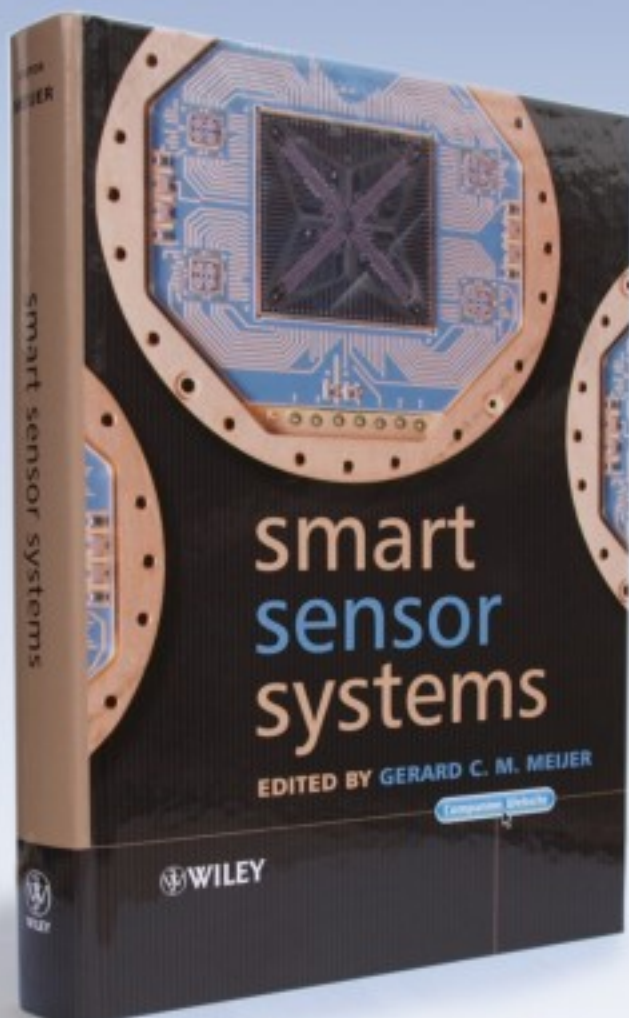
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