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VIBRATION ANALYSIS BASED ON HAMMER IMPACT TEST FOR MULTI-LAYER FOULING DETECTION

Jaidilson Jó da Silva [1,2], *Antonio Marcus Nogueira Lima* [2], *Franz Helmut Neff* [2] *and José Sérgio da Rocha Neto* [2]

[1] Universidade Federal Rural do Semi-Árido, Departamento de Ciências Exatas e Naturais, Mossoro-RN, Brazil,
jaidilson@ufersa.edu.br
[2] Universidade Federal de Campina Grande, Departamento de Engenharia Elétrica, Campina Grande-PB, Brazil,
(amnlima, neff, zesergio)@dee.ufcg.edu.br

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. This work presents preliminary research results of vibrational hammer excitation for easy to use external non-invasive, non-destructive multi-layer fouling detection in pipelines and other large scale duct systems. Data were taken from the vibration amplitude and frequency variation in presence of an inner pipe fouling layer using acoustic accelerometer and microphone detection.

Keywords: Vibrations analysis, hammer impact test, multi-layer 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. A sketch of the two occasionally simultaneously appearing processes is illustrated in Fig. 1, where the corrosion related shrinking of wall thickness is related to the growing fouling layer.

The physico-chemical origin of the fouling process is more complicated. Frequently asphaltic, high molar weight by-products in crude oil or other organic matter react with the inner wall surface, and form a growing layer as a result of a chemical bonding/reaction process. The slowly growing inhomogeneous layer appears hard and mechanically difficult to remove. The deposition rate commonly is very low, and it may take several years until critical thickness values are reached. Fouling in chemical plant duct systems and pipelines accounts for severe problems in plant operation as: reduction of the internal diameter of the tube; reduction of mechanical integrity and strength, reduction of plant operation life time, increase of the applied pressure to maintain flow through-put, crack formation and possibly catastrophic break-up. The associated increase of the energy consumption also comes along with higher operation and maintenance costs.

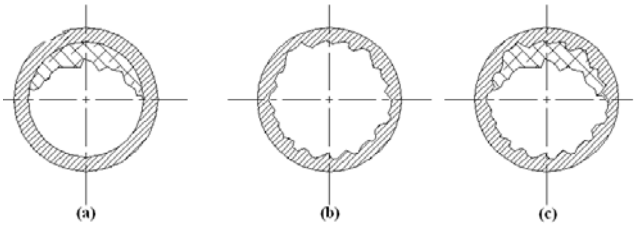


Fig. 1. Cross-section view of tube aging processes with: fouling layer (a), corrosion (b), corrosion and fouling (c).

Large industrial crude oil refining/processing plants are designed as complex tubing structures, with up to several kilometers of interconnected tubes. It therefore is quite difficult and work intensive to quickly and safely identify, exactly localize, clean or replace critical tube sections, to avoid or reduce plant shut down times.

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]. 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 are acoustically detectable by a closely mounted microphone and accelerometer. Using 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.

Ultrasonic recordings towards flaw detection in mechanical structures have been explored earlier. These techniques compares 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 complex structures [7-12]. Based on ideas presented earlier, the acoustic hammer impact has been evaluated in this work towards simplified fouling detection in ducts and pipelines, used for crude oil transport. Here, we analyze variations in vibration amplitude and frequency using both, accelerometer and microphone output signals in presence inner tube fouling layers. The originally present asphaltic fouling layer has been replaced and simulated by a paraffin (resin) film with defined and varying thickness up to 1.0 *cm*, carefully deposited within the test tube.

2. VIBRATION METHOD

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. 2(a) represents a sketch of the experimental set-up using a microphone as detector and Fig. 2(b) shows the experimental set-up using an accelerometer as detector.

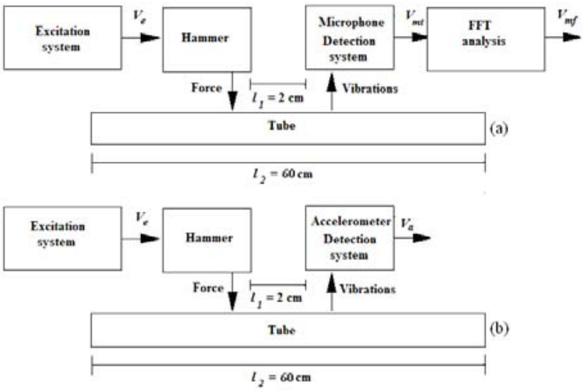


Fig. 2. Sketch of the experimental set-up with: (a) microphone and (b) accelerometer.

Both, a commercial MEMS accelerometer sensor from Analog Devices ADXL 202 and a high quality microphone from Sennheiser 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. A detailed description of the set-up is provided in [13, 14].

3. EXPERIMENTAL RESULTS

A calibration step to define the original acoustic tube signature is initially carried out 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*, a diameter of 10 *cm*, a length of 60 *cm* (l_2), made from galvanized iron, with three layer of fouling (0 *mm*, 5 mm and 10 *mm*) as illustrated in Fig. 3.

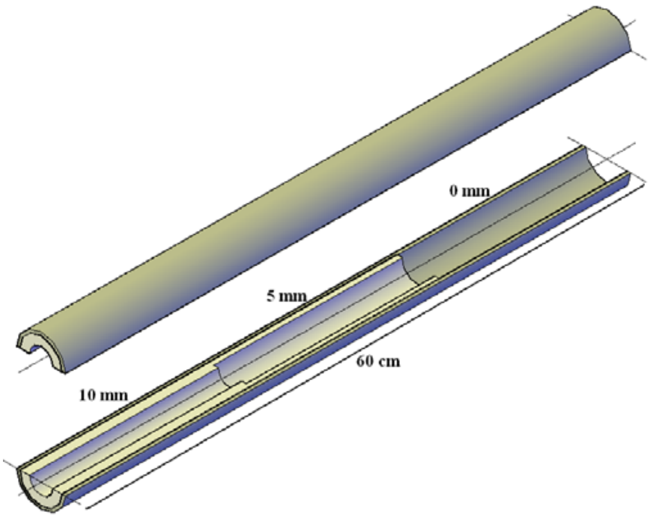
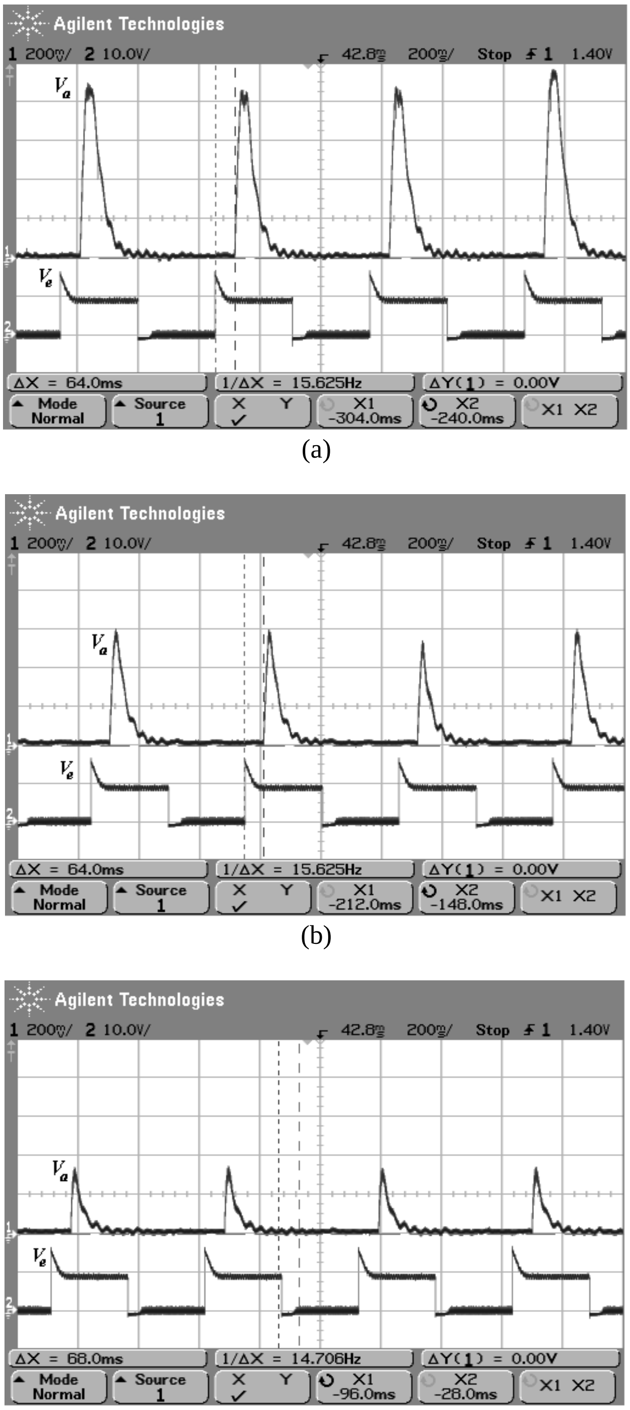


Fig. 3. Transverse view of the tube with three layer of fouling with: 0 *mm*, 5 *mm* and 10 *mm* of resin.

The temporal evolution of the applied hammer impact force load (V_e), recorded by the accelerometer, is illustrated in the lower trace of Figs. 4(a-c). Using a feedback-loop circuit, the signal is used to stabilize the impact frequency and magnitude. The feedback-loop circuit is formed by a DC power supply and for a pulse generator, that excites a coil and it activates the hammer, making the hammer to hit the pipe. The hammer excitement signal frequency is controlled for the pulse generator.

3.1. Obtained results with accelerometer

The monitored and stored accelerometer output signals (V_a) are illustrated in the upper traces of Figs 4(a-c) in absence of fouling, for fouling layer thickness of 5 *mm* and for fouling layer thickness of 10 *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. 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.



(a)

(b)

(c)

Fig. 4. Accelerometer output signals (V_a) in absence of fouling (a), for 5 *mm* of fouling thickness (b) and for 10 *mm* of fouling thickness (c), in the same tube.

Measurements were accomplished with distances, between the hammer impact and the accelerometer and microphone, of 3 *cm* along the tube. The obtained results with the accelerometer are presented in Fig 5.

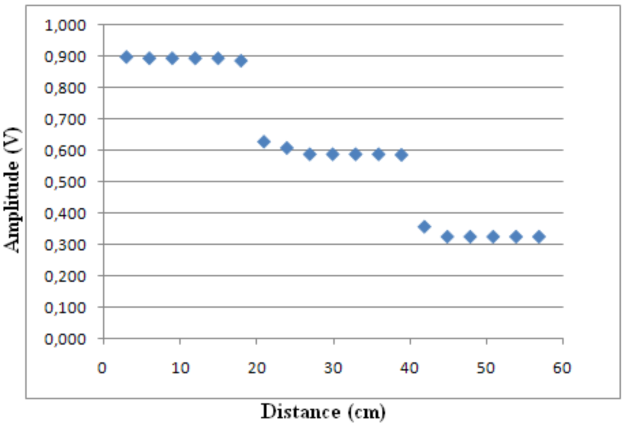


Fig. 5. Obtained results with the accelerometer in a tube with multi-layer fouling.

With the increase of the fouling, there is a reduction in the amplitude, in the tests with the accelerometer. It is also observed the different levels of signals along the tube, that make possible to distinguish the layers inside the tube, in other words, clean tube up to 20 *cm*, tube with 5 *mm* of fouling between 20 and 40 *cm* and a layer of 10 *mm* of fouling (resin) between 40 and 60 *cm*. In this way, it is possible to detected different fouling layers in the same tube.

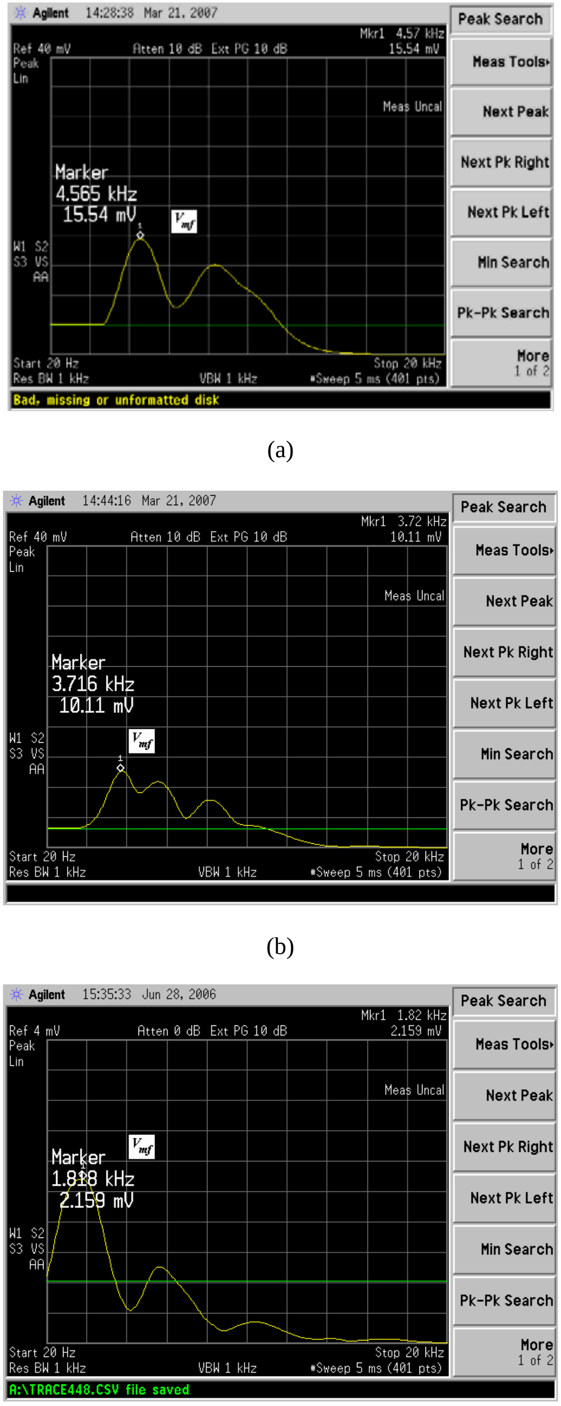
The origin of the signature recorded by the accelerometer is more difficult. We attribute it primly to the transversal deformation wave, which propagates along the tube surface, similar to spreading of a surface water wave. This explanation is supported by our simulation, where the hammer impact causes spatially distributed surface deformations.

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.

3.2. *Obtained results with microphone*

Microphone recordings of the acoustic signatures in the frequency domain (V_{mf}) are shown in Figs. 6(a-c). Fig. 6(a) reveals the signature of a clean test tube. Fig. 6(b) display the waveforms exhibiting a fouling layer thickness of 5 *mm*. Fig. 6(c) display the waveforms exhibiting a fouling layer thickness of 10 *mm*. Data were obtained without keeping liquid (water) in the tube. The frequency spectrum of the clean tube, Fig. 6(a), reveals 3 vibrations modes with resonance frequency in first mode of 4.57 *kHz* (15.54 *mV*). The frequency of the first mode down shifts to 3.72 *kHz* (10.11 *mm*) for the 5 *mm* thick fouling layer in Fig. 6(b). The frequency of the first mode down shifts to 1.82 *kHz* (2.15 *mV*) for the 10 *mm* thick fouling layer in Fig. 6(c).

With the increase of the fouling, there is a reduction in the frequency values, in the tests with the microphone. It is also observed the different levels of signals along the tube, that make possible to distinguish the layers inside the tube, in other words, clean tube up to 20 *cm*, tube with 5 *mm* of fouling between 20 and 40 *cm* and a layer of 10 *mm* of fouling (resin) between 40 and 60 *cm*. In this way, it is possible to detected different fouling layers in the same tube.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(a)

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Fig. 6. Acoustic response V_{mf}: in absence of fouling (a); for 5 *mm* of thick fouling layer (b) and for 10 *mm* of thick fouling layer (c), in the same tube.

The microphone records the acoustic tube signature, due to excitation and propagation of a longitudinal wave, as known from the ringing bell.

The obtained results with the microphone are presented in Fig 7.

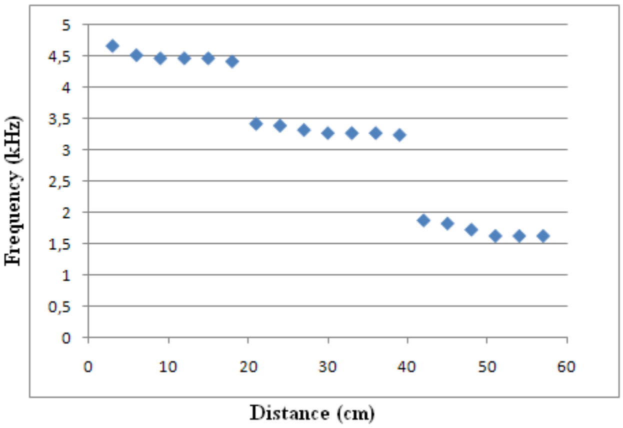

Fig. 7. Obtained results with the microphone in a tube with multi-layer fouling.

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.

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.

4. 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 multi-layer 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.

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