DETECTION OF FAULTS IN PIPE THAT TRANSMITS CRUDE OIL BY VIBRATION SENSING: ANALYTICALLY AND EXPERIMENTALLY

[1]K. I. MOHAMMED, [2]HASSAN MANSOUR RAHEEM, [3]RADHWAN HUSSEIN ABDULZHRAA AL-SAGHEER, [4]HAYDER AL-SARRAF

[1,2,4]Ministry of Oil, Midland Refineries Company, Najaf Refinery, Najaf, Iraq
[3]Department of Computer Science, Faculty of Education for Women, University of Kufa, Najaf, Iraq
E-mail: [1]Karrarmech82@gmail.com, [2]raheemh@oregonstate.edu, [3]radhwan.hu@uokufa.edu.iq, [4]Al-sarraf.2@wright.edu

Abstract - Pipelines are among the most important elements for transporting fluids in the oil industry. Researches show that 55% of the causes of shutdown in oil refineries are due to pipe problems. Oil leakage is a common problem that often results in oil waste, damage, and hazard to public health. The oil industry has invested in equipment to detect and localize leaks along the oil distribution system. The experience in oil distribution companies shows that elimination of crack and reducing erosion–corrosion effects can be achieved by applying strategies that require loss analysis followed by crack detection. In this work, two important cases that cause damage to the pipe, namely, crack and erosion–corrosion, are investigated. In analytical analysis, the mathematical equations for solving the two cases show high compatibility with the solution by examining the vibration sensors for pipeline leakage using an open-source microcontroller panel called Arduino. In experimental analysis, the variation of vibrating sensitivity detects the presence of defects. Therefore, detecting defects in the pipeline before the fault occurs is possible and could prevent large losses. The results show that Arduino was able to detect the defect in the pipe due to the vibration effects. The vibration of the simply supported pipe in the crack and erosion–corrosion cases decreases and increases, respectively.

Index Terms - Arduino, erosion-corrosion, fundamental natural frequency, Vibration in pipe

Symbol	Meaning	Units
a	General solution parameter	
A_p	Pipe cross section area	m^2
A	Fluid cross section area	m^2
b_1	General solution parameter	
b_2	General solution parameter	
c	Critical index	
d_o	Pipe outer diameter	M
di	Pipe internal diameter	M
dc	Crack depth	M
E	Modulus of elasticity	N/m^2
F	Normal force between fluid and pipe per unit length	N/m
g	Gravitational acceleration	m/s^2
I	Second moment of area	m^4
L	Pipe length	M
M	Bending moment	N.m
m_p	Pipe mass per unit length	Kg/m
m_f	Fluid mass per unit length	Kg/m
p_i	Internal pressure	N/m^2
q	Shear stress on the internal surface of pipe	N/m
Q	Transverse shear force in the pipe	l/min
S	Inner pipe circumference	M
T	Tension force in pipe per unit length	N/m
U	Dimensionless fluid velocity	
V	Velocity of fluid	m/sec
V_f	Lateral velocity of fluid	m/sec
x	The position along pipe	M
x_c	The position of crack.	M
X	Dimensionless coordinate	
y	Lateral coordinate	
Y	Dimensionless coordinate	

I. INTRODUCTION

The uses of pipes in transporting liquids is crucial specifically in oil industries because the pipes transport inflammable materials. Researches show that several oil refineries in the world have suffered heavy losses because of cracks and erosion–corrosion effects in pipes. An example is California-based Chevron Richmond refinery, USA, which has a capacity of 250,000 barrels per day. The crude unit was operating as usual, and the operator was on his usual tour when he noticed a leakage from an insulated 8-inch pipe for light gas oil. The fluid temperature was 337 °C. The production manager decided not to shut off the unit due to the small leakage. A decision was made to remove the insulation first. Hydrocarbon gas began to spread after the insulation was removed. The corrosion in the pipe thickness was so severe that could not withstand the pressure of the fluid in pipe. This phenomenon caused catastrophic collapse in the pipe walls after the officials extinguished firewater as a precautionary measure. Hydrocarbon ignited when mixed with air.

Another example that shows the crack effects is Tesoro's Anacortes Refinery in Washington, USA. Explosion and fire occurred in the heat exchanger on April 2, 2010. The heat exchanger used to exchange

heat between low naphtha and crude oil. Thus, the scales that accumulated inside the tube increased the temperature due to the decreasing of the heat transfer rate. The high temperature led to formation of methylene in the heat exchanger. Subsequently, the stresses in the steel caused a large internal crack. Consequently, the 1-inch thickness of the heat exchanger shell broke. Naphtha and hydrogen vapors contacted with air, thereby causing a fire. Generally, the prediction of cracks in pipelines before the disaster happened is necessary. The two aforementioned examples are remarkable introduction that shows the importance of this study.

Jweeg et al. [1] presented the dynamic behavior and the stability of pipes conveying fluid using a modern analysis, such as Galerkin's method to determine the frequencies in various conditions. The results of the proposed analytical solution were verified experimentally and numerically.

Lee et al. [2] presented a nonlinear sample of pipe conveying fluid to analyze the vibration when the pipe was stable at both ends. The nonlinearity of the pipe investigated by using the Lagrange strain-uprooting hypothesis. The coupled nonlinear conditions of movement for the longitudinal and transverse removals were fined on the basis of the expanded Hamilton's guideline.

The natural frequencies also investigated in addition to modeling the mechanical response of the pipe.

Ismail M. [3] reported the natural frequencies for pipes with different boundary conditions using analytical equations. The results showed that many factors could affect the frequency, such as fluid flow and the boundary conditions of the pipe.

Jweeg et al. [4] also experimentally and numerically investigated the effects of cracks in pipes by applying many conditions, such as using different flow velocities, crack positions and sizes. The results stated that the frequency of the fluid transmitted through the cracked pipe decreased due to the increasing in the crack's size.

In this study, we expanded the investigation by studying the effects of the erosion- corrosion and presenting a crack in the pipe that conveys fluid on the fundamental natural frequency theoretically and experimentally. The theoretical values of the natural frequencies determined by using equations, derivations, physical and mechanical scientific laws prepared for this purpose. In addition, a reliable system was utilized for detecting pipeline problems using an accelerometer sensor. Data were analyzed using the Arduino board.

II. THEORETICAL ANALYSIS

The general equation of motion is derived from the development of Euler–Bernoulli beam theory. Fig. 1 shows the forces acting on the fluid element [5].

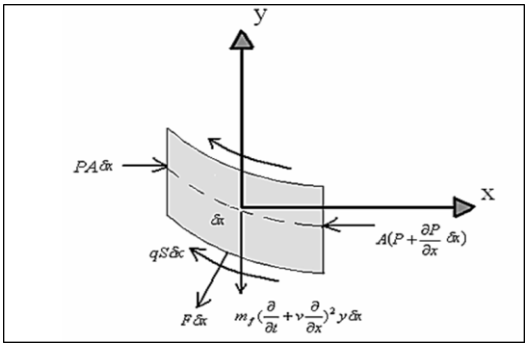


Fig. 1: Force acting on fluid

The fluid velocity can be expressed as follows:

$$V_f = \frac{\partial y}{\partial t} + V\frac{\partial y}{\partial x} \quad (1)$$

The fluid acceleration can be expressed as follows:

$$a_f = \frac{\partial^2 y}{\partial t^2} + 2V\frac{\partial^2 y}{\partial x \partial t} + V^2\frac{\partial^2 y}{\partial x^2} + \frac{\partial V}{\partial t}\frac{\partial y}{\partial x} = \left(\frac{\partial}{\partial t} + V\frac{\partial}{\partial x}\right)^2 y \quad (2)$$

From conditions of equilibrium, the vertical and horizontal forces can be expressed as:

$$F + A\frac{\partial}{\partial x}p\frac{\partial y}{\partial x} + qS\frac{\partial y}{\partial x} + m_f\left(\frac{\partial}{\partial t} + V\frac{\partial}{\partial x}\right)^2 y = 0 \quad (3)$$

$$-A\frac{\partial p}{\partial x} - qS + F\frac{\partial y}{\partial x} = 0 \quad (4)$$

The forces and moments equilibrium on a pipe is shown in Fig. 2.

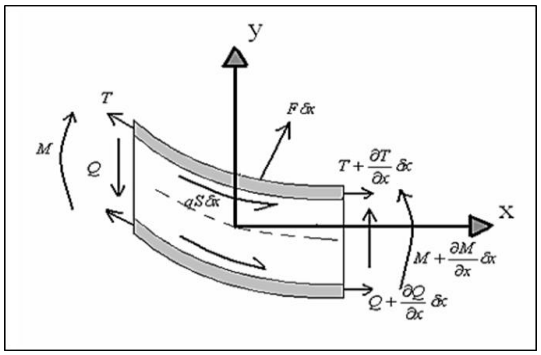


Fig. 2: Force and moment analysis on the pipe

The force balance on the pipe:

$$\frac{\partial Q}{\partial x} + \frac{\partial}{\partial x}\left(T\frac{\partial y}{\partial x}\right) + F + qS\frac{\partial y}{\partial x} = m_p\frac{\partial^2 y}{\partial t^2} \quad (5a)$$

$$\frac{\partial T}{\partial x} + qS - F\frac{\partial y}{\partial x} = 0 \quad (5b)$$

The shear force (Q) is coupled with the bending moment (M) and the pipe distortion by

$$Q = -\frac{\partial M}{\partial x} = -EI\frac{\partial^3 y}{\partial x^3} \quad (6)$$

But in the case of presenting a crack into the pipe, the above equation would be transformed to (7).

$$Q = -\frac{\partial M}{\partial x} = -\frac{\partial}{\partial x}EI\frac{\partial^2 y}{\partial x^2} \quad (7)$$

Combining equation (3), (5) and (7) gives;

$$\left(\frac{\partial^2}{\partial x^2}\mathrm{EI}\frac{\partial^2 y}{\partial x^2}\right)-\frac{\partial}{\partial x}\left((\mathrm{T}-\mathrm{pA})\frac{\partial y}{\partial x}\right)+\mathrm{m_f}\left(\frac{\partial}{\partial t}+\mathrm{V}\frac{\partial}{\partial x}\right)^2 y+\mathrm{m_p}\frac{\partial^2 y}{\partial t^2}=0 \quad (8)$$

Adding equations (3 and 4) and (3 and 6) gives:

$$\frac{\partial(T-pA)}{\partial x}=0 \quad (9a)$$

Integrating equation (9a) gives;

$$T-pA=C \quad (9b)$$

This condition suggests that $(T-pA)$ is free of position along the pipe. At the pipe end where x=L, the tension in the pipe is zero and $p_i=p$ gives $C=-p_iA$. Thus, equation (9b) will be:

$$T-pA=-p_iA \quad (10)$$

Then substituting (10) into (8). The motion equation of pipe conveying fluid for uniform cross section area of pipe equation is obtained.

$$\begin{pmatrix} EI\frac{\partial^4 y}{\partial x^4}+\left(m_fV^2+p_iA\right)\frac{\partial^2 y}{\partial x^2}+ \\ 2m_fV\frac{\partial^2 y}{\partial t\partial x}+m_f\frac{\partial V}{\partial t}\frac{\partial y}{\partial x}+\left(m_f+m_p\right)\frac{\partial^2 y}{\partial t^2}\end{pmatrix}=0 \quad (11)$$

Rearranging equation (11) in dimensionless form as follows:

$$\dddot{\bar{Y}}+(U^2+\gamma)\ddot{\bar{Y}}+2\beta U\dot{\bar{Y}}+\dot{U}\bar{Y}+\ddot{Y}=0 \quad (12)$$

Where:

$$Y=\frac{y}{L},\quad X=\frac{x}{L},\quad U=VL\sqrt{\frac{m_f}{EI}},\quad \gamma=\frac{p_iAL^2}{EI},$$

$$\beta=\frac{1}{2}\sqrt{\frac{m_f}{m_p+m_f}},\quad \tau=\frac{t}{L^2}\sqrt{\frac{EI}{m_p+m_f}}$$

The crack effects on stiffness from equation (11) would be:

$$\begin{pmatrix} \frac{\partial^2}{\partial x^2}EI\frac{\partial^2 y}{\partial x^2}+\left(m_fV^2+p_iA\right)\frac{\partial^2 y}{\partial x^2}+ \\ 2m_fV\frac{\partial^2 y}{\partial t\partial x}+m_f\frac{\partial V}{\partial t}\frac{\partial y}{\partial x}+\left(m_f+m_p\right)\frac{\partial^2 y}{\partial t^2}\end{pmatrix}=0 \quad (13)$$

To calculate the change in stiffness for the cracked pipe [5],

$$EI(X)=\frac{EI_o}{1+Cexp\left(-2\propto\frac{|x-x_c|}{d}\right)}$$

Where:

$$c=\frac{I_o-I_c}{I_c}$$

$$I_o=\frac{\pi(d_o^4-d_i^4)}{64}$$

$$\mathrm{I_c}=\frac{\pi((\mathrm{d_o}-\mathrm{d_c})^4-\mathrm{d_i^4})}{64}$$

$$\propto \text{ is constant equal to}(0.667).$$

In vibration analysis for a cracked pipe, equation above was developed in the domain $0 \le x \le L$, as Fourier series (sum of cosine and sine functions) [5]

$$EI=EI_o\left(A_o+\sum_{n=1}^{\infty}A_n\cos\frac{2\pi nx}{L}+\sum_{n=1}^{\infty}B_n\sin\frac{2\pi nx}{L}\right)$$

Where:

$$A_o=\frac{1}{L}\int_0^L \mathrm{EI(x)dx}=\frac{1}{L}\int_0^L\frac{1}{1+Cexp\left(-2\propto\frac{|x-x_c|}{d}\right)}dx$$

$$A_n=\frac{2}{L}\int_0^L \mathrm{EI(x)}\cos\frac{2\pi nx}{L}\mathrm{dx}=\frac{2}{L}\int_0^L\frac{1}{1+Cexp\left(-2\propto\frac{|x-x_c|}{d}\right)}\cos\frac{2\pi nx}{L}dx$$

$$B_n=\frac{2}{L}\int_0^L \mathrm{EI(x)}\sin\frac{2\pi nx}{L}\mathrm{dx}=\frac{2}{L}\int_0^L\frac{1}{1+Cexp\left(-2\propto\frac{|x-x_c|}{d}\right)}\sin\frac{2\pi nx}{L}dx$$

The general equation in the cracked pipe

$$\begin{pmatrix} EI_o\frac{\partial^4 y}{\partial x^4}\left(A_o+\sum_{n=1}^{\infty}A_n\cos\frac{2\pi nx}{L}+\sum_{n=1}^{\infty}B_n\sin\frac{2\pi nx}{L}\right)- \\ \frac{4\pi n}{L}EI_o\frac{\partial^3 y}{\partial x^3}\left(-\sum_{n=1}^{\infty}A_n\sin\frac{2\pi nx}{L}+\sum_{n=1}^{\infty}B_n\cos\frac{2\pi nx}{L}\right)- \\ \left(\frac{4\pi n}{L}\right)^2EI_o\frac{\partial^2 y}{\partial x^2}\left(\sum_{n=1}^{\infty}A_n\cos\frac{2\pi nx}{L}+\sum_{n=1}^{\infty}B_n\sin\frac{2\pi nx}{L}\right)+ \\ \left(m_fV^2+p_iA\right)\frac{\partial^2 y}{\partial x^2}+2m_fV\frac{\partial^2 y}{\partial x\partial t}+m_f\frac{\partial V}{\partial t}\frac{\partial y}{\partial x}+\left(m_f+m_p\right)\frac{\partial^2 y}{\partial t^2}\end{pmatrix}=0 \quad (13a)$$

However, the erosion-corrosion effects from equation (11)

$$\begin{pmatrix} EI\frac{\partial^4 y}{\partial x^4}+\left(m_fV^2+p_iA\right)\frac{\partial^2 y}{\partial x^2}+ \\ 2m_fV\frac{\partial^2 y}{\partial t\partial x}+m_f\frac{\partial V}{\partial t}\frac{\partial y}{\partial x}+\left(m_f+m_p\right)\frac{\partial^2 y}{\partial t^2}\end{pmatrix}=0$$

The general solution for the vibration equation of the pipe transmitting fluid is,

$$\mathrm{Y(X,T)}=\begin{pmatrix} e^{i(\Omega T-aX)}(A\sinh b_1X+B\cosh b_1X)+ \\ e^{i(\Omega T+aX)}(D\sin b_2X+K\cos b_2X)\end{pmatrix}$$

The boundary conditions of simply supported pipe are:

$$y(0,T)=y''(0,T)=0$$
$$y(l,T)=y''(l,T)=0 \quad (15)$$

Substitute equations (15) in (14) to find the constants and substitute the equation (14) after finding the values of the constants in the main equations (13 a and b) to investigate the effects of the crack and the erosion-corrosion on the natural frequency (Ω).

III. EXPERIMENTAL ANALYSIS

Molecules are either similar or different based on their structures, activities, and distances from one another. In liquids, the distances are smaller and less active but more cohesive than in gases. Thus, liquids take the shape of the container or tube that holds them. Figure 3 shows an oil molecule in a tube.

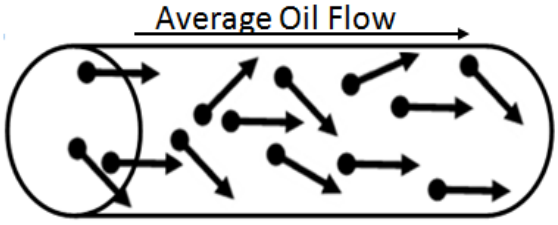


Fig. 3: Visualizing the oil molecules in the tube

A monitoring system that consists of accelerometer sensors (MPU6050), Arduino Uno, and a computer [6,7] is constructed as Diagram 1.

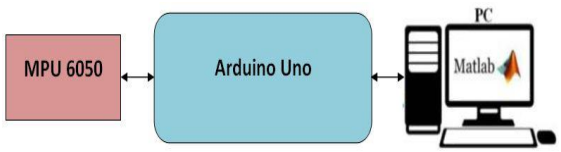


Diagram 1: The proposed system

MPU6050 is installed on the tube. This sensor is sensitive to the frequency generated by the tube vibration as a result of oil flow [7].
MPU6050 is the suitable acceleration sensor for our study because it senses oil molecules in three different directions, namely, X, Y, and Z as Fig. 4.

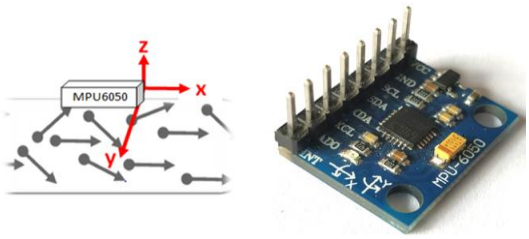


Fig. 4: Longitudinal section of the tube with MPU6050 chip

Arduino Uno is used because it is affordable, suitable for this work, and easy to use in programming. Interfacing MPU6050 with Arduino Uno to measure vibrations in the proposed of this study is feasible. Fig. 5 shows the connection between Arduino Uno and MPU6050.

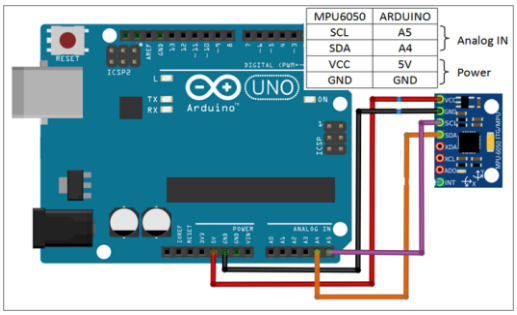


Fig. 5: The interfacing of Arduino uno and MPU6050

MPU6050 sends the signals in their analog state to Arduino Uno via its 6 DOF . This sensor can detect the defects of the tube based on the sensitivity of different frequencies. The latter is generated by the flow of oil in the tube carrier (Fig. 6).

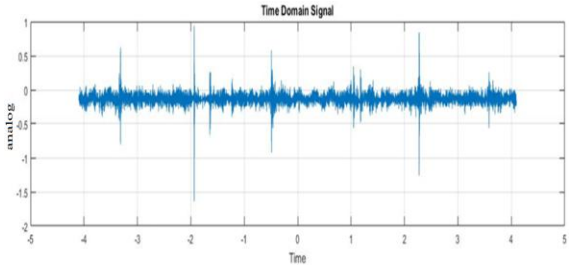


Fig. 6 Illustration of MPU 6050 signals

Arduino Uno, as a processing program, analyzes these signals (Fig. 7).

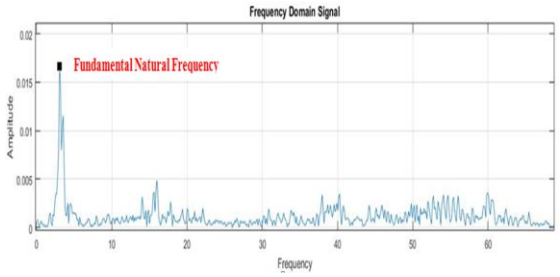


Fig. 7: Illustration of Arduino signals

Then, Arduino Uno passes the signals to the computer via a network designed for this purpose. The signals are converted into values by using computer application programs, such as MATLAB, to be compared with the analytical results.

IV. RESULTS AND DISCUSSION

A. Crack effects

The effects of the crack in the pipe on the fundamental natural frequency was studied with changing the crack location in the pipe (0.2 m, 0.5 m) from the support. The crack dimensions are: length 3 cm, and the depth 4 and 7 cm. All the measurements were taken under the atmosphere pressure. The analytical and experimental measurements are compared as reported in Table 1.

Fig. 8 shows the effects of increasing the crack depth from 4 mm to 7mm on the natural frequency. It can be seen that the natural frequency decreases with increasing the crack length.

Table 1 Comparing the natural frequency between the uncracked and cracked pipe

Uncracked pipe				
Ref.	Crack depth	Analytical (rad/sec)	Experimental (rad/sec)	discrepancy (%)
1	0	72.672	63.466	12.66
Cracked pipe (position of crack 0.25L)				
2	4mm	67.524	59.38	12.06
3	7mm	60.029	53.391	11.01
Cracked pipe (position of crack 0.5L)				
4	4mm	64.883	57.392	11.5
5	7mm	58.028	50.909	12.27

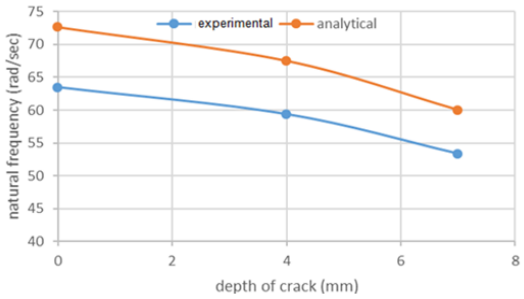


Fig. 8: Crack effects for crack position 0.25L

B. Erosion-corrosion effects

To study the effects of the erosion-corrosion on the natural frequency of the pipe that carries fluid analytically, the thickness of the pipe was reduced from 8mm to 1mm with increment by 2mm to simulate the erosion-corrosion phenomena.
Table 2 reports the results of the response of the pipe.

Table 2: Results of erosion-corrosion in pipe

Erosion-corrosion effects	Analytical (rad/sec)	Experimental (rad/sec)	discrepancy (%)
0	72.672	63.466	12.67
1mm	75.365	64.827	14
3mm	78.726	67.762	13.92
5mm	81.365	70.342	13.54
7mm	87.029	75.927	12.75

The effects of the crack on the fundamental natural frequency is shown in Figs. 8 and 9. The crack growth decreases the frequency in the pipe. Thus, the experimental frequency values of uncracked pipe and cracked pipe is 63.466 and 50.909 rad/sec, respectively. The reduction percentage is 19.68. Therefore, this frequency slightly changed with crack.

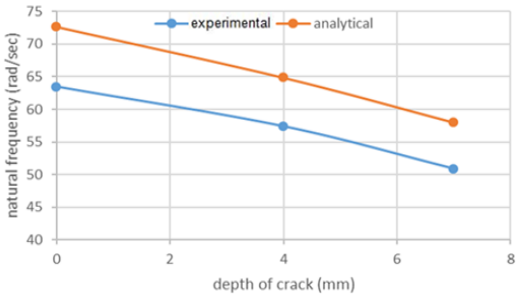


Fig. 9: Crack effects for crack position 0.5L

It can be seen that the erosion–corrosion increases the fundamental natural frequency due to the reduction in pipe thickness (Fig. 10). Thus, the fundamental natural frequency of the analytical solution for the uncracked pipe is 72.672 rad/sec and it is 87.029 rad/sec for the pipe with 7 mm increase in internal diameter, i.e. decreases the thickness of the pipe to 1 mm, Therefore, the increase percentage of frequency is 19.75%.

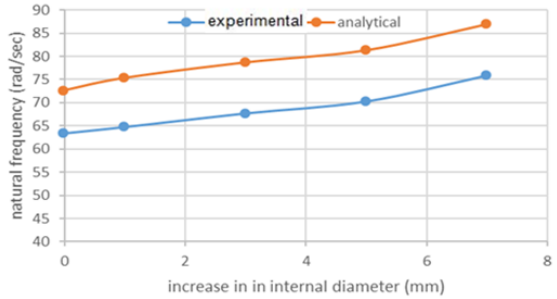


Fig. 10: Erosion-corrosion effects

Finally, the proposed work illustrates that the crack growth decreases the fundamental natural frequency and erosion–corrosion decreases the thickness of the pipe, thereby increasing the fundamental natural frequency. Detecting the presence of faults in the pipe by using sensors to measure frequency before the occurrence of faults is possible and may prevent large losses. Another important fact of the proposed system is its easy installation, in which the base station can be placed at the pipelines and monitoring can be performed by any person with minimal training at the beginning of the system installation.

CONCLUSIONS

The detection of defects in a crude oil pipeline is examined on the basis of two aspects: through analytical solution and experimental method. This study shows that using the Arduino Uno an open source platform is an effective tool for assembling and testing the system. The MPU6050 acceleration sensor also provides valid experimental results. The analytical results of the two cases of this study, i.e. presenting a crack in the pipe and studying the erosion-corrosion effects show good agreements with the experimental results. the findings of this study may be confirmed and verified by applying finite element analysis. The subsequent efforts focus on developing this work to be applied in a practical manner based on the usage of an advanced technology to build an electronic control panel equipped with intelligent tubes and sensors and an immediate decision support system to ensure the safety of oil refineries.

REFERENCES

[1] Jweeg, Muhsin J., and Thaier J. Ntayeesh. "Dynamic analysis of pipes conveying fluid using analytical, numerical and

experimental verification with the aid of smart materials." International Journal of Science and Research 4.12 (2015).

[2] Lee, Su-Il, Jin-Tae Jeong, and Hyeong-Bin Im. "New non-linear modelling for vibration analysis of a straight pipe conveying fluid." Transactions of the Korean Society of Mechanical Engineers A 26.3 (2002): 514-520.

[3] ISMAIL, MAHMUD RASHEED. Evaluating the Dynamical Behavior and Stability of Pipes Conveying Fluid. Diss. Ph. D. Thesis AL-Nahrain University, mechanical engineering, (2011).

[4] M. J. Jweeg, E. Q. Hussein and K. I. Mohammed. "Effects of Cracks on the Frequency Response of a Simply Supported Pipe conveying Fluid", International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS Vol:17 No:05.(2017).

[5] Jweeg, Muhsin J., Emad Q. Hussein, and Karrar Ibrahim Mohammed. "A suggested analytical solution for dynamic behavior of a cracked pipe conveying fluid." International Journal of Energy & Environment 9.1 (2018).

[6] Varanis, Marcus, et al. "Instrumentation for mechanical vibrations analysis in the time domain and frequency domain using the Arduino platform." Revista Brasileira de Ensino de Física 38.1 (2016).

[7] Ismail, M. I. M., Rudzidatul Akmam Dziyauddin, and Noor Azurati Ahmad Samad. "Water pipeline monitoring system using vibration sensor." Wireless Sensors (ICWiSE), 2014 IEEE Conference on. IEEE, (2014).

★★★