Modeling Flow-Induced Vibration of Pipes in Oil Industry: A Case Study

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Abstract: - The flow-induced vibration is a critical problem in the Oil & Gas industries. It has been observed that vibration generated in the pipework may lead to cyclic stresses, which can result in incidents of leakage. Factors that affect flow-induced vibration are many. Properties and characteristics of the pipe material as well as the fluid carried in the pipelines, physical connection and setup of pipelines, dynamics of the flowing fluid, are just some of the many variables that can affect the vibration, which need to be considered when modeling flow-induced vibration in pipes. This work aims to investigate the validity of a mathematical model to predict flow-induced vibration in piping systems. The results can be utilized to forecast the failure of the piping system as a result of flow-induced vibration. The real-time vibration data were investigated in a real oil industry station. In this work, flow-induced vibration measurements were carried out, and the frequency and acceleration of vibration were analyzed. Carbon steel and GRE pipes were tested at different sizes, flow rates, and boundary conditions. The frequency and acceleration of vibration were recorded using a 3-axis vibration sensor. A mathematical model is presented to estimate flow-induced vibrations in pipes. Moreover, comparisons of the experimental results with the theoretical model were presented to validate the accuracy of the model in predicting the flow-induced vibrations in the pipes.

Keywords: - Condition monitoring, oil Pipelines, preventive maintenance, Carbon steel pipes, GRE pipes, and Natural frequency

1. INTRODUCTION

Excessive vibration leads to increased wear and tear of the parts and inaccurate readings from the sensors. It is also one of the main causes of leakages in pipelines and explosions in refineries and petrochemical plants. The vibrations are measured by determining the amplitude of the vibration. The higher the amplitude, the greater the vibration. The vibrations of maximum amplitude are encountered at a special condition called resonance, which occurs when the natural frequency of the object under vibration is very close to or the same as the exciting frequency. The vibrations at resonance lead to catastrophic failure of the equipment. Thus, the vibration analysis of the piping system is required to be done to avoid leakages in the pipe and to help engineers choose the correct clamping system in the right locations in order to reduce the vibration-induced failures in the pipeline

Flow induced Vibration is a serious problem in Oil & Gas industries, and repeatedly occurring vibration in the pipeline will lead to leakages, which would eventually cause danger to the lives of the workers in the Oil field. The economic impact of piping vibration analysis is to provide a long-life period for the pipe and help to reduce the cost of maintenance. Also, leakage of oil leads to the pollution of soil and the atmosphere. Moreover, vibration in the piping system may cause leakages leading to fire accidents, which may result in the loss of human life. In the oil industry, the piping system provides transport for a wide range of substances such as petrochemicals and water. The flow through the pipeline must be non-stop, twenty-four hours a day, throughout the year. This non-stop flow leads to repeated stress due to vibration. If the maximum stress that a pipe's metallic material can withstand for an infinitely large number of sinusoidal reversed cycles of loading is reached, failure due to fatigue will occur [1]. Fatigue is one of the major causes of leaks and failures of pipelines. [1]. Finite element software through modal analysis was applied to monitor conditions of piping vibration under operation [2]. The concept of modal testing has been adapted for hydraulic pipeline systems and demonstrated for a straight pipeline [3]. Finite element analysis was applied to determine the critical velocity in the pipeline, which can be implemented using a distributed vibration sensing system for the Oil and Gas industry [4].

Another advantage of modeling the pipelines using software and a mathematical approach is the ability to investigate different types of supports through setting appropriate boundary conditions [5]. A model based on vibration measurement was created to detect the leakages and to indicate the areas where there is a maximum possibility of leakage [6]. A combination of computational fluid dynamics and finite-element modeling was also developed for assessing and diagnosing multiphase-flow-induced vibration problems in hydrocarbon-production piping systems [7]. In-line and cross-flow coupling vibration response characteristics of a marine viscoelastic riser subjected to two-phase internal flow were also studied using extended Hamilton's principle, and the model was validated through comparisons with the published experiment and numerical simulation results [8]. It has been reported that according to the standard of the gas industry, when the vibration speed reaches 18 mm/s referred to as an emergency vibration level. Similarly, when the vibration speed exceeds 41 mm/s, it is referred to as the alarm vibration level. Also, for pipeline sections more than 0.5m, the vibration displacement span is restricted to 0.5 mm [9].

Flow induced vibration model has been developed for the case of clamped ends of a free pipe section, and mathematical expressions were developed for natural frequency, pipe deflection, critical velocity, and maximum stress due to vibration [10]. In this work, experimental results were obtained and compared with the flow-induced vibration model developed by [10], which was found to be in good agreement. This work, including experimental measurement of different sizes and materials of pipeline vibration, was carried out at Mina' Al Fahal Oil refinery located in Oman. The station consists of a network of various pipelines with different materials such as Carbon steel and GRE.

2. MATHEMATICAL MODEL FOR FLOW-INDUCED VIBRATION IN A PIPE

Flow-induced vibration of pipe sections due to internal fluid flow has been a common phenomenon in industrial plants and pipelines. In the case of natural vibrations, the stress across the cross-section of pipelines can be determined using the following equation [7]:

$$\sigma = \Upsilon_0 \frac{EIy''}{W(Z)'} \tag{1}$$

where: y is the displacement amplitude, σ is a permissible stress in the pipe metal, EI is the bending rigidity of the pipe, Υ_0 is the allowable amplitude of vibration, and $W(Z)$is a moment of resistance in the pipeline along the flow axis(Z).

The natural frequency of the beam is given below, where the mass of the beam is replaced by the mass of the pipe, and the pipe is assumed to be simply supported [9]:

$$\omega_n = \beta^2 \sqrt{\frac{EI}{ML^4}} \tag{2}$$

The standard values for β^2 are as follows: for clamp support 4.73, for simply supported 3.142, for clamp and simply support 3.927, and for clamp with fixed support 1.875.

$$F_{flex} + m\frac{d^2y}{dt^2} + F_{cent} = 0$$

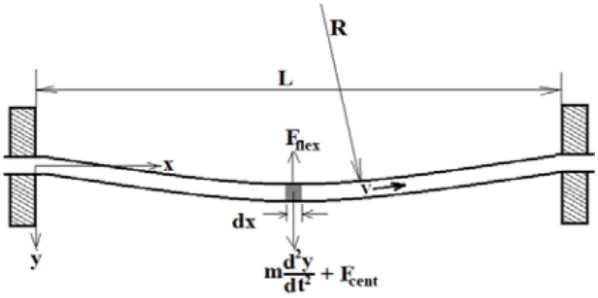

Figure 1. Schematic diagram of vibrating pipe section [8]

The governing equation for the flow-induced vibration will be presented for a clamped support pipe as shown in Figure 1, where analysis can be simplified with the following assumptions while deriving the governing equation [8]:

- The whole pipe section has a homogeneous cross-section, and fluid is flowing through at an average velocity.
- Supports are rigid clamps.

- Vibration amplitude is much less than the free length of the pipe.
- Vibrating section is strong enough to resist transitioning into the second mode

where,

F_{flex} – Flexural reaction
F_{cent} – Centripetal force
m – Mass of flowing fluid
$\frac{d^2y}{dt^2}$ – Fluid flow acceleration

We know that from mechanics,

$$F_{flex} = EI\frac{d^2}{dx^2}\left(\frac{1}{R}\right) \quad (3)$$

and

$$F_{cent} = m_f V^2\left(\frac{1}{R}\right) \quad (4)$$

where R is the radius of curvature, and from calculus, we can write the radius of curvature as,

$$\left(\frac{1}{R}\right) = \frac{\frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{\frac{3}{2}}} \quad (5)$$

Substitute these values in the governing equation, and from the assumption of small deflection in a structurally strong pipe section, the equation simplifies to [8]:

$$EI\frac{d^2}{dx^2}\left[\frac{\frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{3/2}}\right] + m_f V^2\left[\frac{\frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{3/2}}\right] + m_{tot}\frac{d^2y}{dt^2} = 0 \quad (6)$$

Subject to boundary conditions (BCs)

$$y(0,t) = 0$$
$$y(L,t) = 0$$
$$\frac{dy(0,t)}{dx} = 0$$
$$\frac{dy(L,t)}{dx} = 0$$

and the initial condition

$$y(x,0) = 0$$

Assuming a solution of the form:

$$y(x,t) = Y(x)\sin\omega t$$

with Y(x) assumed to be an exponential function:

$$Y(x) = Ce^{\lambda x}$$

The solution in the form of a Polynomial by series expansion can be written as below [8],

$$y(x) = B_1 + B_2x + B_3x^2 + B_4x^3 + B_5x^4 \quad (7)$$

Applying the boundary conditions

$$B_1 = B_2 = 0$$
$$B_3 = B_5L^2$$
$$B_4 = -2B_5L$$

The solution is now [8],

$$y(x,t) = B_5(x^2L^2 - 2x^3L + x^4) \times sin\,(wt) \quad (8)$$

where B_5 and w are yet to be found

Later, the average values of centripetal force and the average value of deflection would be used to eliminate x.

Then, the Governing equation is simplified to calculate w and peak amplitude [8].

$$EI(24B_5) + m_f V^2\frac{d^2y(x)}{dx^2} - m_{tot}w^2y(x) = 0 \quad (9)$$

The peak value of deflection Y(x), which occurs in the middle, is therefore,

$$y(x) = y\left(\frac{L}{2}\right) = \frac{B_5L^4}{16} \quad (10)$$

The points at which direction changes have zero centripetal force and average inverse of curvature peaks in the different zones, we can calculate constant B_5, and this value is an estimate local to the regions [8]

$$B_5 = \frac{4.6024}{L^3} \quad (11)$$

The equation can be written to calculate ω[8],

$$EI(24B_5) + m_f V^2(-0.037123m_f B_5L^2) - m_{tot}w^2\left(\frac{B_5L^4}{16}\right) = 0 \quad (12)$$

then flow natural frequency can be expressed as [8],

$$\omega = \sqrt{\frac{16(24EI - 0.037123m_f V^2L^2)}{m_{tot}L^4}} \quad (13)$$

where,

- E is the Modulus of elasticity for the pipe material, in MPa
- I is the Moment of Inertia for a Circular section in m^4
- m_f is the Mass of flowing fluid inside the pipe, in kg/m
- L is the Length of the pipe for the measured location, in m
- V is the flow velocity of the fluid, in m/s
- M_{tot} is the Total mass i.e., the Sum of the mass of the flowing fluid and pipe, in kg/m

Equation (13) will be primarily used to estimate the natural frequency of pipes under experimental investigation.

Figure 2. Sensor locations on a 6" pipeline

3. EXPERIMENTAL SETUP

Experimental setup and measurement were carried out at Mina' Al Fahal Oil refinery located in Oman. The station consists of a network of various pipelines with different materials, such as Carbon steel and GRE, that carry oil, oil mixture, and water. The pipelines' vibration was investigated, and the frequency and acceleration of vibration were analyzed. The frequency and acceleration of vibration were recorded using a 3-axis wireless accelerometer, which was placed on the surface pipes (with different materials and different sizes) to record vibration data of the pipe under study. Figure 2 shows points at which measurements were taken from the 6'' GRE pipe, where the red dots indicate the locations of placing the sensor. A 20 cm space was taken between two successive points. The Coriolis flow meter shown in Figure 3 was used to measure the flow rate of a fluid flowing through the pipe. This measurement will later be compared with the theoretical frequencies calculated from equation (13). The same measurements for vibration were repeated for the carbon steel pipe. The number of readings was taken along the 6 " Carbon steel (CS), 3" CS, in the same way it was carried out for the 6" GRE pipe.

Figure 3. Sensor locations on a 6" pipeline

4. RESULTS AND DISCUSSION

This section presents the experimental measurement of flow-induced vibration at different locations on a number of pipes within the refinery station. Measurements were carried out at Mina' Al Fahal Oil refinery located in Oman. Figure 4 shows a sample of measured vibration for the CS 3" pipe, where the peak vibration takes place at 45 Hz with a magnitude of 0.066 m/s^2.

For example, the frequency of vibration for the 6" pipe GRE is 79.5 Hz at a flow rate of 24.2± 0.1 m^3/hr, while the frequency of vibration for CS 6" was 48.7 Hz (± 6%) at a flow rate of 25.6 ± 0.4 m^3/h.

Theoretical flow-induced vibration values based on equations (12) were also calculated and compared with the experimental results. For example, a GRE pipe at the given flow rate is expected to vibrate at a frequency of 79.5 Hz for the span length of 2.6 m. This value is very close to the measured frequency value (77.9 Hz). Figure 5 present comparison between measured and calculated vibration frequencies for 6'' inch GRE, 6"-inch CS, and 3"-inch CS pipes.

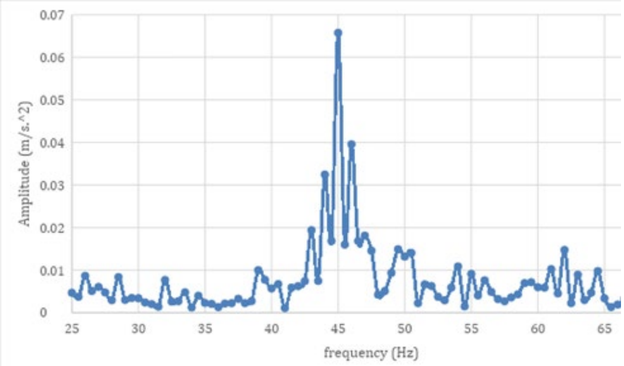

Figure 4. Measured vibration for CS 3" pipe

Table 1. Data related to the 6'' GRE Pipe

Density of GRE/CS Pipe, kg/m^3	1550
Density of crude oil, kg/m^3	800
Length of pipe at measuring Location, m	2
Natural Freq. pipe with Clamped Supports, Hz	77.892
Peak Displacement (m)	0.00004
Maximum Acceleration, m/s^2	9.611

Table 2. Data related to the 6'' CS Pipe

Density of CS Pipe, kg/m^3	7860
Density of crude oil, kg/m^3	800
Length of pipe at measuring Location, m	1.2
Natural Freq. pipe with Clamped Supports, Hz	43.954
Peak Displacement (m)	0.00012
Maximum Acceleration, m/s^2	9.724

Table 3. Data related to the 3'' GRE Pipe

Density of CS Pipe, kg/m^3	7860
Density of crude oil, kg/m^3	800
Length of pipe at measuring Location, m	0.6
Natural Freq. pipe with Clamped Supports, Hz	47.314
Peak Displacement (m)	0.0001
Maximum Acceleration, m/s^2	9.611

The parameters used in the calculation of vibration frequency and acceleration of different pipes are presented in the Tables. 1, 2, and 3.

The frequency of vibration along with the flow rate, for CS 6", CS 3", and GRE 6" pipes is presented in Table 4.

Table 4. Acceleration and frequency value of 6" CS (Carbon steel), 3" CS, and 6" GRE pipes

Reading	Pipe	Distance (cm)	Frequency (Hz)	Flow Rate (m^3/hr)
R1	CS 6"	20	50	24.1
R2	CS 6"	40	50	24.2
R3	CS 6"	60	49.5	24.2
R4	CS 6"	80	46	24.2
R5	CS 6"	100	48	24.3
R6	CS 3"	120	45	24.3
R7	GRE 6"	140	79.5	24.4
R8	GRE 6"	160	79.5	24.5
R9	GRE 6"	180	79.5	24.5
R10	GRE 6"	200	79.5	24.6
R11	GRE 6"	220	79.5	24.7
R12	GRE 6"	240	79.5	24.7
R13	GRE 6"	260	79.5	24.8
R14	GRE 6"	280	79.5	24.9
R15	GRE 6"	300	79.5	25.1
R16	GRE 6"	320	79.5	25.0

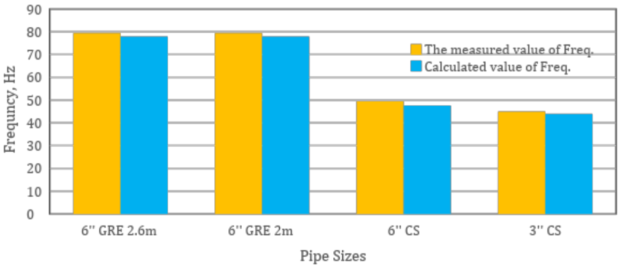

Figure 5. Comparison between measured and calculated vibration frequencies

Figure 5 present comparison between measured and calculated vibration frequencies for 6'' inch GRE, 6”-inch CS, and 3”-inch CS pipes.

Theoretical induced vibration was also compared with the measured values for the case of carbon steel pipes (6” and 3”).

5. CONCLUSIONS

The flow-induced vibration is a critical problem in the Oil & Gas industries since it introduces fatigue damage, which eventually leads to leakages in the pipe. Therefore, flow-induced vibration of the piping system is to be estimated based on operation conditions (e.g. flowrate of fluid), type of pipe materials, and characteristics of the flowing fluid.

In this work, a model to predict the amplitude and frequency of flow-induced vibration in oil pipelines was presented and verified experimentally. At a given flow rate of 24.1 to 25.1 m^3/hr, the amplitude and frequency of vibration were measured and compared with the theoretical values for 6” CS, 3” CS, and 6” GRE pipes. Results from the mathematical model were compared with the measured results and show high agreement with a maximum error of 4%. There are certain parameters to identify the severity of vibrations, but the most critical parameter is the critical velocity. The model can then be extended to predict the frequency and amplitude of flow-induced vibration of pipes. The result can also be applied to control the flow characteristics and pipes’ materials to avoid fatigue failure and dangerous resonance frequency of pipes.

REFERENCES

[1] Kong, K.; Khoo, S.; Ong, Z.; Eng, H.; Ismail, Z.; Chong, et al. Failure Analysis of Flow-Induced Vibration Problem of In-Serviced Duplex Stainless Steel Piping System in Oil and Gas Industry. *Mater. Res. Innov***.** 2014, *18* (sup6), S6-417–S6-422.

[2] Mironov, A.; Doronkin, P.; Priklonsky, A.; Kabashkin, I. Condition Monitoring of Operating Pipelines with Operational Modal Analysis Application. *Transp. Telecommun. J.* 2015, *16* (4), 305–319.

[3] Mikota, G., et al. Modal Testing of Hydraulic Pipeline Systems. *J. Sound Vib.* 2017, *409*, 256–273. doi:10.1016/j.jsv.2017.08.001.

[4] Yan, Q., et al. Distributed Vibration Sensing System for Oil and Gas Pipelines Based on COTDR and BP Neural Network. In *26th International Conference on Optical Fiber Senso***rs**, OSA Technical Digest; Optica Publishing Group, 2018; paper WF42.

[5] Grant, I. Flow Induced Vibrations in Pipes: A Finite Element Approach. *ETD Arch.* 2010, 633.

[6] Xueping, C.; Jinming, F.; Wenwu, Y.; Yinghui, L. In-Line and Cross-Flow Coupling Vibration Response Characteristics of a Marine Viscoelastic Riser Subjected to Two-Phase Internal Flow. *Shock Vib.* 2021, Article ID 7866802, 27 pages.

[7] Victorovna, M. L. Vibration Strength of Pipelines. In *InTech*; 2018. doi:10.5772/intechopen.72794.

[8] Udoetk, E. Internal Fluid Flow Induced Vibration of Pipes. *J. Mech. Des. Vib.* 2018, *6* (1), 1–8. doi:10.12691\jmdv-6-1-1.

[9] Dai, H. L.; Wang, L.; Qian, Q.; Gan, J. Vibration Analysis of Three-Dimensional Pipes Conveying Fluid with Consideration of Steady Combined Force by Transfer Matrix Method. *Appl. Math. Comput.* 2012, *219* (5), 2453–2464.

[10] Sulaima, M. F.; Abdullah, F.; Bukhari, W. M.; Ali, F. A.; Nasir, M. N. M.; Yahya, A. B. Oil and Gas Offshore Pipeline Leak Detection System: A Feasibility Study. *Appl. Mech. Mater.* 2014, *699*, 891–896; Trans Tech Publications, Ltd.