Stability Analysis of Fluid-Conveying Beams using Artificial Intelligence

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Abstract— This paper employs artificial intelligence in predicting the stability of pipes conveying fluid. Field data was collected for different pipe structures and usage. Adaptive Neuro-Fuzzy Inference System (ANFIS) model is implemented to predict the stability of the pipe using the fundamental natural frequency at different flow velocities as the index of stability. Results reveal that the neuro-fuzzy model compares relatively well with the conventional finite element method. It was also established that a pipe conveying fluid is most stable when the pipe is clamped at both ends but least stable when it is a cantilever.

Keywords— ANFIS, fatigue, fundamental frequency, natural frequency, stability

1 Introduction

Pipes are of great importance in both domestic and industrial fields including oil and gas (especially fluid conveying pipeline as in Figure 1), aerospace, nuclear, industrial processing, as well as power generation and transmission. They are used for conveying various fluids from one point to another. The transmission of fluid in pipes results in induced vibrations due to the inherent properties of the fluid. Fluid-induced vibrations resulting from deflection experienced on the walls of the pipes causes high instability and fatigue of the pipes. This instability can lead to events which are not suitable for the state of life and property in nuclear reactors, mines, oil pipelines, heat exchangers and other pipe using industries.

Studies have shown that pipes become prone to instability and fatigue when the first fundamental natural frequency becomes zero (Baohui et. al., 2012).The effects of the system parameters on pipe behaviour were studied by (Modarres-Sadeghi & Païdoussis, 2009). Clearly, the natural frequency of a pipe decreases with increasing velocity of fluid flow (Grant, 2010). The need of properly understanding causes of instability to pipes conveying fluids is of great importance. These instabilities sometimes cost so much to the general system.

Fig. 1: Alaska oil pipeline (Source: google.com)

The natural frequency of a pipe reduces as flow velocity increases; this is because as flow velocity increases, the pipe stiffness reduce, causing a drop in the fundamental natural frequency of the fluid-conveying beam. In general, the entire stability of the pipe conveying fluid depends on the natural frequency of the pipe and its critical velocity (Chellapilla & Simha, 2008).

The deployment of Artificial Intelligence into many fields has brought endless possibilities to solving problems. Previous researchers have shown how it has been used to predict, monitor and control vibration problems especially as experienced in pipes conveying fluids. Zahra et al. (2014) used the artificial neural network to monitor vibration of Steam Turbine in a Nuclear Power Plant.

A lot of research work has aimed at understanding the mechanics of pipes conveying fluid. The concept for modelling the interaction between fluid and structures from aero and hydro-elasticity has shown the applicability of computational methods for problems involving flow-induced vibration (Zilian, 2014). Besides, experimental studies have shown the correlation between the fluid flow in a pipe and the resulting vibrations.

Investigations have shown that pipe vibration levels are proportional to the fluid flow rate (Safari & Tavassoli, 2011). Computational analysis was used to determine the critical fluid velocity that induces the threshold of pipe instability when conveying fluid (Grant, 2010; Seo et al.(2005); Ritto et al.(2014)). Farshidianfar, (2012) described the instability experienced in pipes as a result of the fundamental natural frequency vanishing. In their own works, Hakim and Abdul Razak, (2011), and Kao and Hung (2005) employed Artificial Neural Networks (ANNs) in the dynamic stability analysis of damaged and undamaged structures.

The present study employed ANFIS in predicting the stability of a given pipe when conveying a given fluid at a given fluid flow speed. Different boundary condition scenarios were also looked at.

2 Mathematical and Intelligent Models

2.1 Equation of Motion for Fluid-Conveying Beam

Mathematical models for the dynamics of a straight fluid-conveying beam are developed. These models were used to derive the fundamental natural frequency, critical fluid velocity and natural frequency.

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The system under consideration is a straight, tight and of finite length pipeline, with fluid passing through it. The following assumptions were made in the pipe analysis:

- The effects of gravity, the damping coefficient of the material, shear strain and rotational inertia were ignored.
- The pipeline is assumed horizontal.
- The pipe is inextensible.
- The lateral movement of y(x,t) is small, and with significant length, when compared with the diameter of the pipe so that theory Euler-Bernoulli is applicable for the description of vibration bending of the pipe.
- There is uniform fluid velocity along the cross section of pipe.

The equation for a single span pre-stressed pipeline transporting fluid depends on the distance x and time t according to the beam theory

$$EI\frac{\partial^4 y}{\partial x^4} + m_p\frac{\partial^2 y}{\partial t^2} = f_{int}(x,t) \quad (1)$$

Where EI represents the bending stiffness of the pipe, m_p is the mass per unit length of the pipe, and f_{int} represents the inside force acting on the pipe. The internal fluid flow is assumed a plug flow, so all points of the fluid have the same velocity relative to the pipe. This is a reasonable assumption for a turbulent flow profile. Due to that, the inside force can be written as:

$$\left\{f_{int} = -m_f\frac{\partial^2 y}{\partial t^2}\bigg| x = Ut\right\} \quad (2)$$

Where m_f is the mass per unit length of the fluid, while U is the fluid flow velocity. The total acceleration can be decomposed into local acceleration, Coriolis and centrifugal.

$$\begin{aligned}\left\langle m_f\frac{\partial^2 y}{\partial t^2}\bigg| x = Ut\right\rangle &= m_f\left\langle\frac{\partial}{\partial t}\left(\frac{\partial y}{\partial t} + \frac{\partial y}{\partial x}\frac{\partial x}{\partial t}\right)\bigg| x = Ut\right\rangle \\ &= m_f\left\langle\frac{\partial}{\partial t}\left(\frac{\partial y}{\partial t} + \frac{\partial y}{\partial x}\mathrm{U}\right)\bigg| \mathrm{x} = \mathrm{Ut}\right\rangle \\ &= \mathrm{m_f}\left\langle\frac{\partial^2 \mathrm{y}}{\partial \mathrm{t}^2} + 2\mathrm{U}\frac{\partial^2 \mathrm{y}}{\partial \mathrm{x}\,\partial \mathrm{t}} + \mathrm{U}^2\frac{\partial^2 \mathrm{y}}{\partial \mathrm{x}^2}\right\rangle\end{aligned} \quad (3)$$

The internal fluid causes a hydrostatic pressure on the pipe wall

$$T = -A_i P_i \quad (4)$$

Where A_i is the internal cross sectional area of the pipe and P_i is the hydrostatic pressure inside the pipe. Considering that the total acceleration composed of local, Coriolis and centrifugal acceleration, the resulting equation describing the oscillations of the pipe is given by equations (5) and (6) (Mediano & García, 2014)

$$EI\frac{\partial^4 y}{\partial x^4} + (m_f U^2 - T)\frac{\partial^2 y}{\partial x^2} + 2m_f U\frac{\partial^2 y}{\partial x \partial t} + (m_f + m_p)\frac{\partial^2 y}{\partial t^2} = 0 \quad (5)$$

Equation (5) can be written as

$$EI\frac{\partial^4 y}{\partial x^4} + (\rho A - T)\frac{\partial^2 y}{\partial x^2} + \rho A\left(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x}\right)^2 y + M\frac{\partial^2 y}{\partial t^2} = 0 \quad (6)$$

Where M is the addition of the mass per unit length of both pipe and fluid, ρ is fluid density and A is the cross sectional area of the pipe. The shear stress is given by equation (7).

$$A\frac{\partial \rho}{\mathrm{dx}} + \vartheta \mathrm{A_i} = 0 \quad (7)$$

Where ϑ is the shear stress on the pipe and $\mathrm{A_i}$ is the inner perimeter of the pipe. Eliminating the shear stress at the pipe end where $x = L$, the tension in the pipe is zero and the fluid pressure is equal to ambient pressure. Thus $p = T = 0 \; at \; x = L$. Hence,

$$\rho A - T = 0 \quad (8)$$

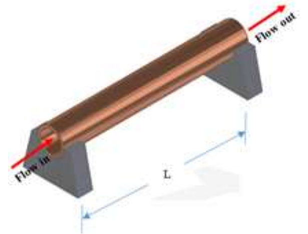
giving the equation of motion for a free vibration of a fluid conveying beam as equation (9).

$$EI\frac{\partial^4 y}{\partial x^4} + \rho A v^2\frac{\partial^2 y}{\partial x^2} + 2\rho A v\frac{\partial^2 y}{\partial x \partial t} + M\frac{\partial^2 y}{\partial t^2} = 0 \quad (9)$$

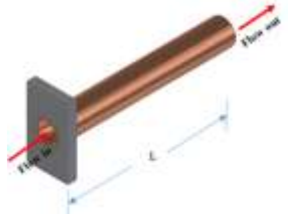
Each of the terms in equation (9) represent a force acting on the system where $EI\,\partial^4 y/\partial x^4$ is the stiffness, $\rho A v^2\,\partial^2 y/\partial x^2$ is the centrifugal force, $2\rho A v\,\partial^2 y/\partial x \partial t$ is the Coriolis force and $M\,\partial^2 y/\partial t^2$ is the inertial force.

2.2 Critical Velocity and Natural Frequency for Different Pipe Supports

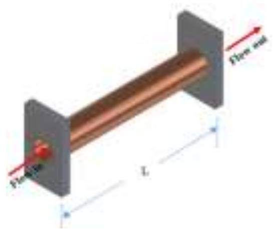
Consider a pipe of length, L, an outside diameter d, thickness, t and modulus of elasticity, E that has fluid flowing with a velocity v through its inner cross-section. Figure 2 are different types of beam supports.



Simply-supported Pipe Conveying Fluid



Cantilever Pipe Support



Clamped-clamped Pipe Conveying Fluid

Fig. 2: Different Pipe Supports

The expressions for critical velocity and natural frequency for different support types of fluid-carrying pipe are given (Grant, 2010) in Table 1.

Ojetola *et al.*, (2011) highlighted that instability is associated with zero fundamental natural frequency for all pipe support configurations.

Table 1. Critical Velocity and Natural Frequency for Different Pipe Supports

Support type	critical velocity, V_C	natural frequency, ω_n
simply-supported	$V_c = \left(\frac{(\pi)^2}{L^2}\right)\sqrt{\frac{EI}{M}}$	$\omega_n = \left(\frac{\pi}{L}\right)\sqrt{\frac{EI}{\rho A}}$
cantilever beam	$V_c = \left(\frac{(1.875)^2}{L^2}\right)\sqrt{\frac{EI}{M}}$	$\omega_n = \left(\frac{1.875}{L}\right)\sqrt{\frac{EI}{\rho A}}$
clamped-clamped	$V_c = \left(\frac{(2\pi)^2}{L^2}\right)\sqrt{\frac{EI}{M}}$	$\omega_n = \left(\frac{2\pi}{L}\right)\sqrt{\frac{EI}{\rho A}}$

I is the moment of inertia; ρ is the density of the fluid flowing through the pipe; A is the cross-sectional area of the pipe.

2.3 Implementing Neuro-Fuzzy Model for Predicting Stability

The neuro-fuzzy model, widely known as ANFIS is a popular computing framework based on the concepts of fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning. The ANFIS is a class of adaptive networks which are functionally equivalent to FIS (fuzzy inference system) (Cruz & Mestrado, 2009).

In this paper, the first-order Sugeno fuzzy model is used to generate fuzzy rules from a set of input-output data pairs. Among many FIS models, the Sugeno fuzzy model is the most widely applied one for its high interpretability and computational efficiency and built-in optimal and adaptive techniques. Data for pipes of different configurations and at different fluid flow velocities were obtained. About hundred different pipes used in various industries were gathered and used to generate the training data.

A parametric study was conducted for the three different pipe supports using the various pipe parameters (such as the pipe thickness and outer diameter) from field research. The aim was to generate training data used to train the ANFIS model to predict the stability of these various pipes when the fluid flowing through it is the desirable Nigerian bonny light crude oil with an average density of 854.5 kg/m^3.

3 Results and Discussion

For the sake of this work, instability sets in when the frequency ratio goes to zero, which also denotes the fundamental natural frequency is zero. The parameters for steel pipe used for this study are shown in Table 2.

Table 2. Material Parameters for the Sample Pipe

Modulus of elasticity E (GPa)	Number of elements	Length of pipe L (m)	Density of fluid ρ_f (kg/m^3)	Density of Pipe ρ_p (kg/m^3)
207	150	30	854.5	8000

Assuming the parameters in Table 2 holds for all the pipes in question, the variable parameters becomes the thickness, outer diameter, and the fluid flow velocity. Therefore, using MATLAB program the other parameters are derived, that is the critical velocity, natural frequency and fundamental natural frequency thus, hence Tables 3, 4 & 5 are generated. A pipe with an outer diameter of 375 *mm* and thickness of 18.5 *mm* is considered for the three boundary conditions.

Table 3. Various Flow Velocities and Fundamental Natural Frequencies for Simply-Supported Pipe

Velocity	Velocity Ratio	Fundamental Natural Frequency	Frequency Ratio (ω/ω_n)
0	0	1.2233	1
15	0.275042	1.106299	0.904356
30	0.825125	0.599745	0.490268
60	1.100167	0	0

If the pipe is simply-supported, the natural frequency and critical velocity which remains constant will be 54.53717*m/s* while the natural frequency will be 1.2233 *rad/s.*

Table 4. Various Flow Velocities and Fundamental Natural Frequencies for Cantilever Pipe

Velocity	Velocity Ratio	Fundamental Natural Frequency	Frequency Ratio (ω/ω_n)
0	0	3.1033	1
30	0.328473	2.8072	0.904585
60	0.656947	1.620594	0.522216
90	0.98542	0	0

If the pipe is Cantilever, the natural frequency and critical velocity will be 91.33 *m/s*, while the natural frequency will be 3.10 *rad/s*.

Table 5. Various Flow Velocities and Fundamental Natural Frequencies for Clamped-Clamped Support

Velocity	Velocity Ratio	Fundamental Natural Frequency	Frequency Ratio (ω/ω_n)
0	0.00	7.0142	1
50	0.38	5.1954	0.740719
80	0.61	2.8654	0.408526
130	1.00	0	0

For the Clamped-clamped, the natural frequency and critical velocity will be 130.59 *m/s*, while the natural frequency will be 7.014 *rad/s*.

The parameters computed in Tables 3, 4, 5 will be derived for the whole hundred pipes in question, and will be used as training data for our ANFIS model. From our Tables, it could be seen that the critical velocity and natural frequency are different for different support types. As such, different models will be designed for various support type. As stated earlier, the key to predicting the stability of the pipe is the frequency ratio. This simply implies that the instability of the pipe increases as this dimensionless ratio tends to zero.

The three different designed models share similar design features. The only changing thing will be their values and limits in the membership function. For simplicity and accuracy, a Seugino type FIS was used for the model with only two inputs and output. This was chosen since some of the parameters vary directly with each other. An example is the natural frequency and the critical velocity. Therefore, the selected inputs were the natural frequency and the fluid flow velocity. Each input has its membership function. Table 6 shows how the training data was uploaded to the ANFIS model.

Figure 3 shows that the first input has three membership function segments while the second input consists of four membership function segments. Therefore, the number of rules and output membership function segments created is equal to twelve each. The output is frequency ratio with different membership function value based on the values of the input. After designing the model, the input data and output data were uploaded. These were used to train the network severally. The test data was uploaded with the model working and able to predict the stability of pipe.

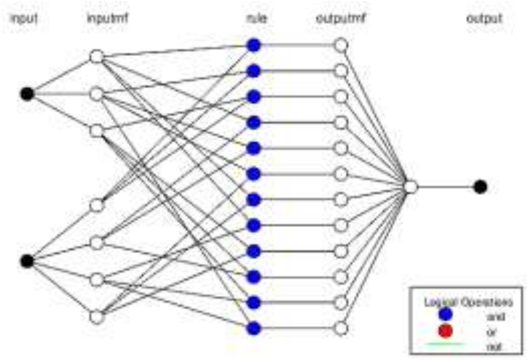


Fig. 3: ANFIS model for predicting stability of fluid conveying beam

Figure 4 illustrates the effect of fluid flow velocity in the frequency ratio of a vibrating pipe conveying fluid for different beam supports. The frequency ratios are equal to 1 when the speed is 0. At very low velocity, $v < 5\ m/s$, there is an initial drop in frequency ratios before taking a parabolic path and resting at different critical velocities. Results reveal that the critical velocity (i.e. when the frequency ratio is 0) is highest for the clamped-clamped support (with $v = 140\ m/s$); followed by the simply-supported beam (with $v = 90\ m/s$), then the cantilever beam (with $v = 45\ m/s$).

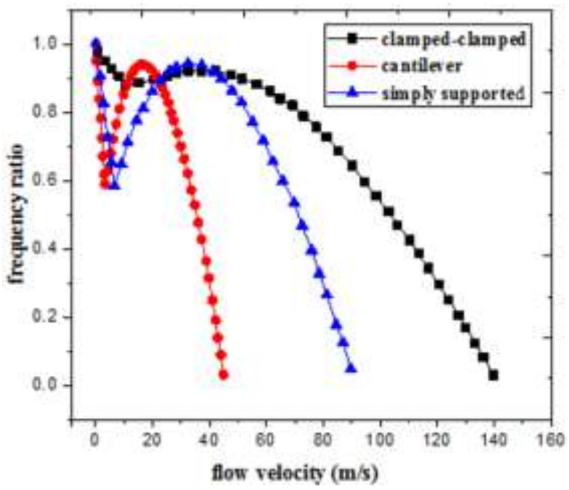


Fig. 4: Frequency ratio against fluid flow velocity for different beam supports

Figure 5 demonstrates the variation of frequency ratios with natural frequencies of a vibrating pipe conveying fluid for different beam supports. The figures exhibit Sigmund formation. It is observed that the maximum frequency ratio is highest for the clamped-clamped support (at $\omega_n = 8\ rad/s$), followed by the simply-supported pipe (at $\omega_n = 5.5\ rad/s$), and finally, the cantilever support (at $\omega_n = 2\ rad/s$). It can also be seen that the clamped-clamped support has the highest range of natural frequencies, followed by the simply-supported, and then the cantilever support that has the lowest range; showing that clamped-clamped beams are more stable than the cantilever and the simply-supported pipes.

Table 6. Generation of the Training Data

Velocity	Velocity Ratio	Fundamental Natural Frequency	Frequency Ratio (ω/ω_n)
0	0.00	7.0142	1
50	0.38	5.1954	0.740719
80	0.61	2.8654	0.408526
130	1.00	0	0

The training data was a 400x3 matrix formed by computing the frequency ratio for four different fluid flow velocity steps that was used.

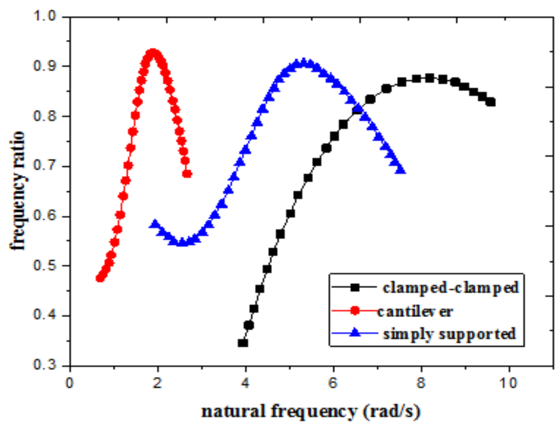


Fig. 5: Frequency ratio against natural frequency for different beam supports

The result using neuro-fuzzy method is now compared with the finite element model. Data of five different pipes gotten from the field were used as sample. The pipes are different basically in their diameter to thickness ratio. The fluid considered is also the bonny light crude with a density of 854.4kg/m^3 for flow over a length of 30m. Finite element programme is used to solve for the frequency ratio with increasing velocity for the different pipe configurations. Here, only the simply-supported beam is considered.

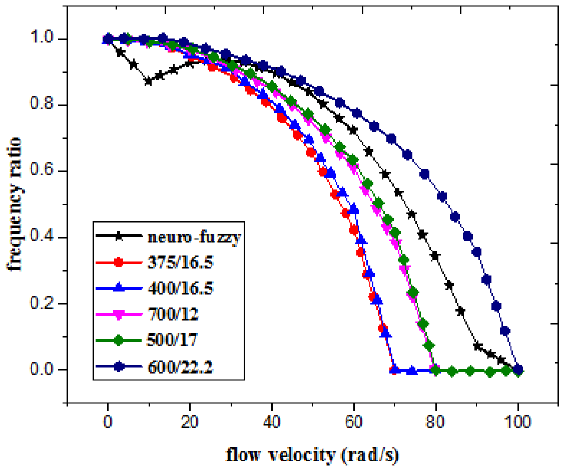


Fig. 6: Comparative analysis of frequency ratio against natural frequency for various pipe structures using finite element method and neuro-fuzzy model

Figure 6 shows the comparative graph of the two models. The graph reveals that the result from the neuro-fuzzy model compared relatively well with that of the finite element method

4 Conclusion

In this work, an intelligent system that can predict the stability of fluid conveying beams using the fundamental natural frequency as the primary index of stability has been designed. It was implemented using Sugeno ANFIS structure in MATLAB. It has been shown that the critical velocities for the different pipe support types were different. Results reveal that the clamped-clamped support shows the widest range of the fundamental natural frequency against that of other support types of comparable frequency ratios; hence, has more stability than the simply-supported, and then cantilever support. The comparative analysis of the neuro-fuzzy model with the conventional finite element method indicates that both correlated very well.

Therefore, an intelligent model has been developed that can accurately predict the stability of conveying fluid pipe and could be useful in operational scenarios to estimate both the design life and maintenance schedule/costs of pipelines.

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