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Influence of wire winding on the dynamic characteristics of a pulsatile fluid conveying copper tube

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ABSTRACT

Fluid-conveying copper tubes find usage in many applications, including refrigeration, heat exchangers, fuel supply lines and air conditioning. This makes it essential to explore the dynamic properties of fluid conveying copper tubes for the dynamic control of such systems. In this study, the development of a modal testing set up for studying tubes conveying pulsatile fluids and the testing techniques are discussed. The natural frequencies are discovered by performing experimental modal analysis. The influence of internal excitation due to pulsatile fluid flow was extracted using operational modal analysis. By examining the deflection amplitudes, the influence of wire winding on the dynamic behaviour of the tube is analyzed. A stiffness addition phenomenon due to wire winding is identified. This study proposes a possible vibration amplitude control method by employing wire winding in specific configurations.

1. Introduction

Fluid-conveying tubes are common components in numerous industries as they find their applications in refrigeration, air conditioning, heat exchangers, transport lines, fuel supply lines etc. copper tubing is frequently utilized in such applications because of its greater strength, long life and non-corrosive qualities. Excessive vibration has been a common issue in pipelines, which can subsequently affect the life span of the piping system. Continuous momentum exchange between the tube wall and the internally flowing fluid causes disturbance to the system. These fluid–structure interactions can cause the tube to vibrate even in the absence of any external excitation, due to the internal flow conditions and tube geometry. It is important to explore the dynamic properties of fluid conveyance tubes for the dynamic control of such systems.

The dynamic behaviour of tubes is influenced by fluid–structure interaction, according to various studies on the subject. By defining governing equations and delineating various anchoring and flow conditions, Paidoussis et al. [1] has provided a comprehensive explanation of fluid–structure interaction and its impact on the dynamics of fluid-conveying tubes. He demonstrates that when flow velocity increases, the instability area for fluid conveyance tubes grows. The possibility of instability at particular frequencies and perturbation amplitude ranges were identified. The water hammer theory, which is a result of fluid–structure interaction, was described by Lavooij et al. [2], and various coupling processes were modelled. In order to determine the dynamic reaction of structures that contain liquids, Jalali et al. [3] conducted numerical and experimental research. They discovered that the effect of liquid on structure goes beyond the mass effect. The hydrodynamic mass effect and damping of tubes with internal flow were studied by Matuck et al. [4]. The dynamics of the tube were found to be significantly affected by the added mass of flowing fluid. Analytical study was done by Faal et al. [5] on the flexural vibration of a self-excited, completely elastic-supported tube caused by internal flow. It was found that the tube’s natural frequency rose as the stiffness rose, but fell as the velocity rose.

El Najjar et al. [6] investigated the dynamic stability of pipes that convey fluids, subjected to additional point masses and springs. The study concluded that the amount of added mass and its location has significant influence on the dynamics of the tube. Unnikrishnan et al. [7] devised an experiment to ascertain the dynamic characteristics of a horizontally fixed pre-stretched tube. They provide a thorough description of the factors impacting modal parameter estimate as well as precautions to be followed throughout the experiment. A study on the tube dynamics under internal pulsing flow excitation was carried out by

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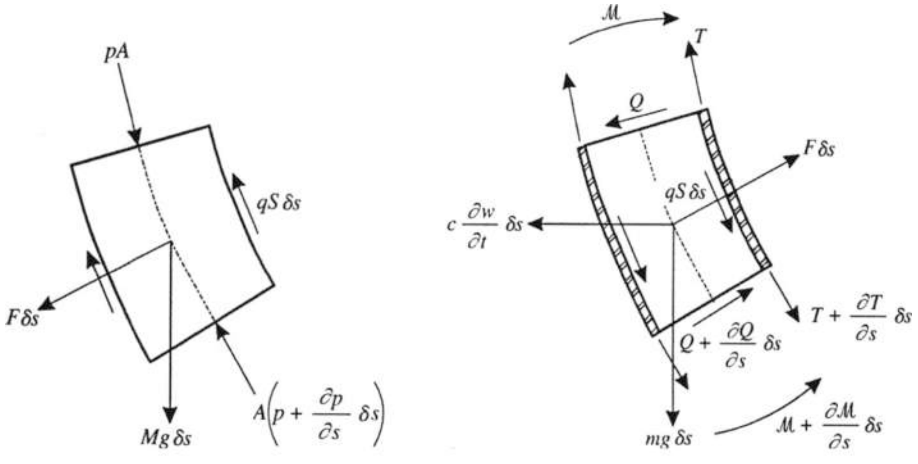

(a) (b)

Fig. 1. (a) Forces on an element δs of the fluid; (b) forces and moments on an element of the tube [1].

Krishna et al. [8]. For the purpose of estimating modal parameters of a fluid conveyance tube, various excitation approaches were investigated.

Studies on wire winding on fluid conveying tubes show that it has an impact on the interactions between the fluid and the structure. Ya-Xia et al. [9] investigated an inner wall spiral corrugation technique for improving heat transfer. Spiral corrugation's pitch can be decreased to enhance heat transfer within the tube. Zhang et al. [10] researched the impacts of spiral winding on the heat exchanger for cryogenic systems, and they discovered that spiral wound effects on heat transfer rate and pressure drop help to increase the refrigeration effect. In their study on the impact of the quantity of wire wrappers on the flow field, Lin et al. [11] found that the wrapped wire shields the rod from vibrations. Wire wrapping effects of pressure vessels were researched by Cardenas et al. [12]. Wire winding improved the vessel's stability and decreased the likelihood of crack propagation. With wire coil inserts, Kim et al. [13] investigated vibration in two-phase flow. Due to stronger turbulence and pressure fluctuations, the wire coil with a lower pitch length vibrated more. In their analysis of flow-induced vibrations and deformations of fuel rods, Santis et al. [14] took the influence of wire spacers and different working fluids into account. When the influence of the wire spacer is highlighted, it is discovered that the dynamics of the wire-wrapped rod differ significantly from those of the unwrapped rod.

The above literature review highlights the importance of controlling vibrations that arise due to fluid structure interactions. Various researchers have made efforts in finding ways to control such vibrations. Yet the influence of wire winding on the dynamics of internally excited fluid conveyance tubes is less explored. This work examines the scope of vibration control by investigating the influence of wire winding on the dynamic response of a horizontally placed copper tube conveying a pulsatile fluid, experimentally. Experimental set up for studying the dynamics of a fixed–fixed copper tube conveying water is prepared for external as well as internal excitation methods. A comparison of the dynamic response of the tube with wire winding around its external surface for different wire winding configurations is reported. A phenomenon of stiffness addition due to wire winding is identified and a possible vibration control method is proposed.

2. Theory

A uniform slender pipe with a length of L, an internal perimeter of S, a flow area of A, a mass per unit length of m, a flexural rigidity of EI, and small lateral motions of w(x, t), is taken into consideration by Paidoussis [1] to convey a fluid with uniform mean axial flow velocity U and mass M.

The fluid element shown in Fig. 1(a) is subject to pressure forces (pA) brought on by frictional losses, reaction forces (qS) brought on by the wall shear stress, and gravity forces (Mgs) as well as reaction forces (Fs) of the pipe on the fluid. Transverse shear force Q, bending moment $\mathcal{M}$, and longitudinal tension T are all applied to the pipe element in Fig. 1 (b). As a result of friction with the fluid surrounding it, the pipe experiences damping, where c is the coefficient of viscous damping. Internal dissipation is also accounted in the pipe element, with a stress–strain relation $\sigma = E\varepsilon + E^*(d\varepsilon/dt)$, E^* being the coefficient of viscoelastic damping. The general equation for small lateral motions can be expressed as,

$$\begin{aligned}&(E^*\frac{\partial}{\partial t}+E)I\frac{\partial^4 w}{dx^4}+\left\{MU^2-T+PA(1-2v\delta)-\left[(M+m)g\right.\right.\\&\left.\left.-M\frac{\partial U}{\partial t}\right](L-x)\right\}\frac{\partial^2 w}{\partial x^2}+2MU\frac{\partial^2 w}{\partial x\partial t}+(M+m)g\frac{\partial w}{\partial x}+c\frac{\partial w}{\partial t}+(M+m)\frac{\partial^2 w}{\partial t^2}\\&=0\end{aligned} \tag{1}$$

which is based on beam theory and plug flow assumptions with small changes in fluid velocity along the radial direction. v is the Poisson ratio. $\delta = 0$ implies no constraint to axial motion and $\delta = 1$ implies restricted axial motion at $x = L$. The Eq. (1) can be simplified to,

$$EI\frac{\partial^4 w}{dx^4}+MU^2\frac{\partial^2 w}{\partial x^2}+2MU\frac{\partial^2 w}{\partial x\partial t}+(M+m)\frac{\partial^2 w}{\partial t^2}=0 \tag{2}$$

if U is constant and the effects of dissipation, pressurisation, gravity and tensioning are either neglected. The terms in the Eq. (2) stand for flexural restoring force, centrifugal force, Coriolis force and inertia force respectively. Any modifications to the tube's mass or stiffness could alter the tube's dynamic responsiveness.

3. Methodology

Experimental set up is developed to conduct modal analysis on a fixed–fixed copper tube that conveys water. To identify the natural frequency of the tube, Experimental Modal Analysis (EMA) set up is prepared incorporating an external electromagnetic shaker excitation mechanism. Operational Modal Analysis (OMA) set up is prepared incorporating a pulse generating mechanism to find the deflection amplitudes of the tube in order to study the influence of internal excitation.

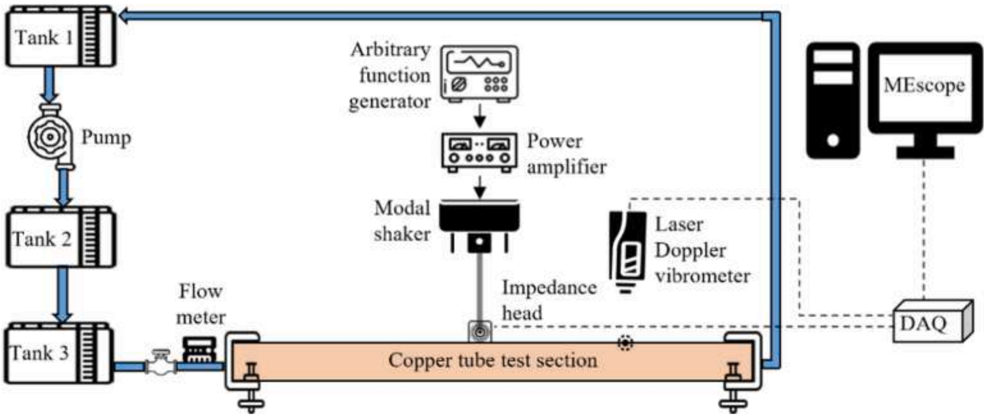

Fig. 2. EMA set up for testing the dynamics of the copper tube.

Table 1
Dimensions of copper tube.

Dimensions	Value (mm)
Length	1000
Outside diameter	12.7
Inside diameter	10.92
Thickness	0.89

3.1. *Experimental modal analysis (EMA)*

The EMA test facility is shown in Fig. 2. It comprises of a fluid circulation system, an excitation mechanism, a vibration sensor and an analysis software. The fluid circulation systems consist of a water pump to carry water to the overhead tanks positioned to maintain a constant head. The fluid flow is managed by a rotary valve. The inlet flow velocity is measured using the Portaflow 300 Ultrasonic flowmeter.

The copper tube is horizontally clamped at both ends. The dimensions of the copper tube used for the test are given in Table 1.

The tube is externally excited using the electromagnetic modal shaker, Sentek MS200. The excitation signal is generated using Keysight 33500B arbitrary function generator and amplified using Sentek LA-500 power amplifier. Through a stinger rod, a Dytran 5860B impedance head is linked to the shaker and fastened to the tube in order to monitor the excitation force.The dynamic response was acquired at marked points using Polytec LS400 Laser Doppler Vibrometer (LDV). Signals from the impedance head and LDV are acquired through NI DAQ 4431 dynamic signal analyzer and further processed using vibration analyzer software MEscope Version 21.0.4.29. The factors affecting the modal parameter estimation during EMA are optimized for the experimental system as identified by Unnikrishnan et al [7]. By examining the frequency response curve, the natural frequency of the copper tube may be determined from EMA.

3.2. *Operational modal analysis (OMA)*

The test facility for conducting OMA is shown in Fig. 3. It employs a pulse generating mechanism which consists of a rotary valve and a VFD controlled motor to generate fluid pulses. Controlling the flow pulse rate at the tube’s natural frequency, as determined from EMA, brings the tube into resonance. LDV is employed to capture the tube response at each test condition. Data acquisition and post processing is done in vibration analyzer software MEscope Version 21.0.4.29. The data acquisition and signal processing methods to conduct OMA on the tube conveying a pulsatile flow were adapted from Krishna et al. [8].

Details of different copper wires used to wind the copper tube are

Table 2
Properties of the different types of wires wound on the copper tube.

Wire diameter (mm)	Length (mm)	Mass (gram)
0.55	1035	2.2
0.95	1035	6.57
1.3	1035	12.3
1.6	1035	18.63
2	1035	29.12

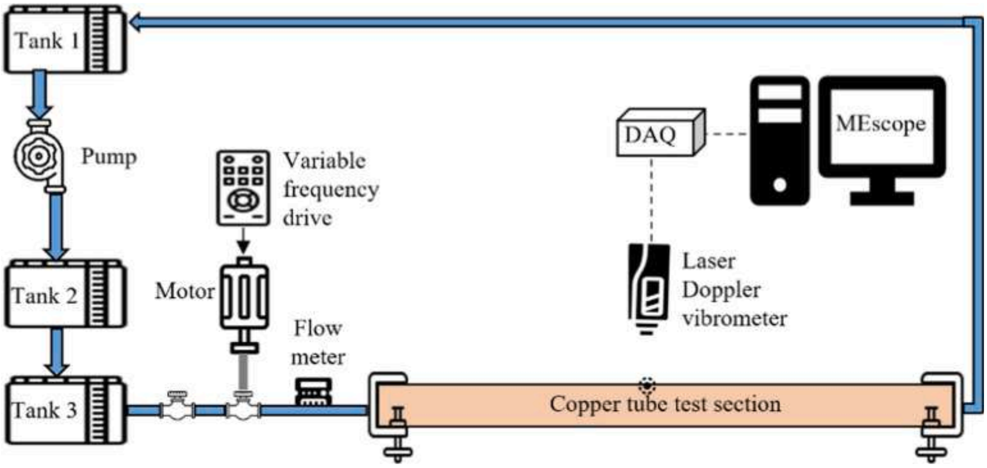

Fig. 3. OMA set up for testing the influence of wire winding on the dynamics of the copper tube subjected to pulsatile flow.

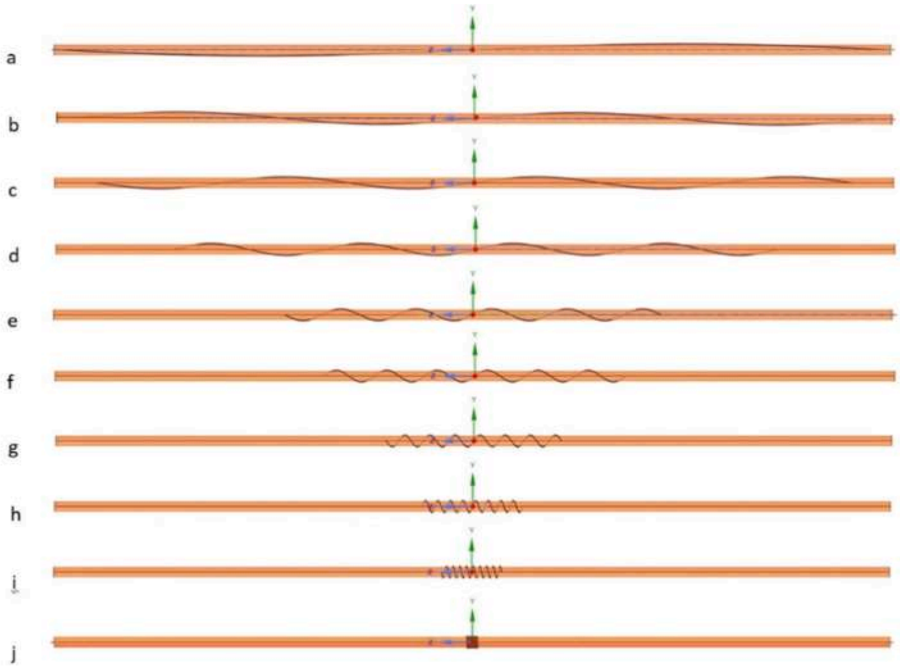

Fig. 4. Schematic representation of the copper tube with different test configurations.

Table 3
The details of the different test configurations shown in Fig. 4.

Configuration	Pitch length (mm)
a	1000
b	500
c	250
d	125
e	62.5
f	31.2
g	15.6
h	7.8
i	3.9
j	Point mass

listed in Table 2..

To better understand the impact of wire winding with varied pitch lengths, a number of tests are carried out. A schematic representation of the various test configurations considered for this study is given in Fig. 4.

The details of the testing configurations are listed in Table 3.. The deflection amplitudes of each case are measured and analysed.

4. Results and discussions

The dynamic characteristics of the copper tube due to external excitation was identified from the frequency plots obtained by conducting EMA. Fig. 5 represents the frequency response plot from EMA of empty copper tube. Modes of the tube are identified from the peaks appearing on the frequency response function and the drop in the coherence plot corresponding to it [15]. It is determined that 25 Hz is the empty copper tube's first fundamental frequency.

4.1. Influence of working fluid on the dynamics of the tube

When the tube is filled with water, it can be read from Fig. 6 that the frequency response function peaks of mode 1 and mode 2 are shifted towards left. The first fundamental frequency from frequency plot was identified as 22 Hz. This decrease in fundamental frequency indicates the influence of the working fluid on the dynamic behaviour of the tube. Also, the decrease in the size of mode 1 peak indicates an increase in damping due to the added mass effect of the working fluid.

4.2. Influence of flow pulsation

Resonance was induced by passing a 22 Hz pulsatile fluid through the copper tube whose first fundamental frequency was identified as 22 Hz from EMA. During OMA, LDV measured the vibration response of the tube in terms of velocity. This signal is further integrated to displacement and is then converted to the frequency domain, Fig. 7. The maximum amplitude of the vibrations of the fluid conveying copper tube is identified as 0.02563 mm for a 22 Hz pulse rate at a flow velocity of 19.13 cm/s.

4.3. Influence of wire winding

To study the overall influence of wire winding on a fluid conveying tube, all wire sections mentioned in Table 2, are wound around the copper tube one at a time and the experiment is carried out. All the experiments used configuration a, mentioned in Fig. 4.

The vibration amplitude is plotted against the diameter of the wound wires at different flow velocities in Fig. 8. The vibration amplitude is observed to be less than that of a tube without wire winding. Similarly, at higher flow velocities of 30.98 cm/s and 40.91 cm/s, this trend was observed. When the wire diameter is increased, the amplitudes of vibration are further reduced. As the wire diameter is increased, added mass is also increased hindering the motion of the tube causing the reduction in the amplitude of vibration. These observations indicate that winding a wire on a fluid conveying tube influences its dynamics which is evident from the reduction in the amplitude of vibration of the tube.

4.4. Influence of stiffness addition

To investigate the influence of stiffness addition alone when the copper tube is wound with a copper wire, a copper wire of fixed mass, diameter and length is wound around the tube in decreasing pitch length configurations. The 1.3 mm diameter wire as mentioned in Table 2 is used in this study in configurations shown in Fig. 4. The results of the same are plotted in Fig. 9.

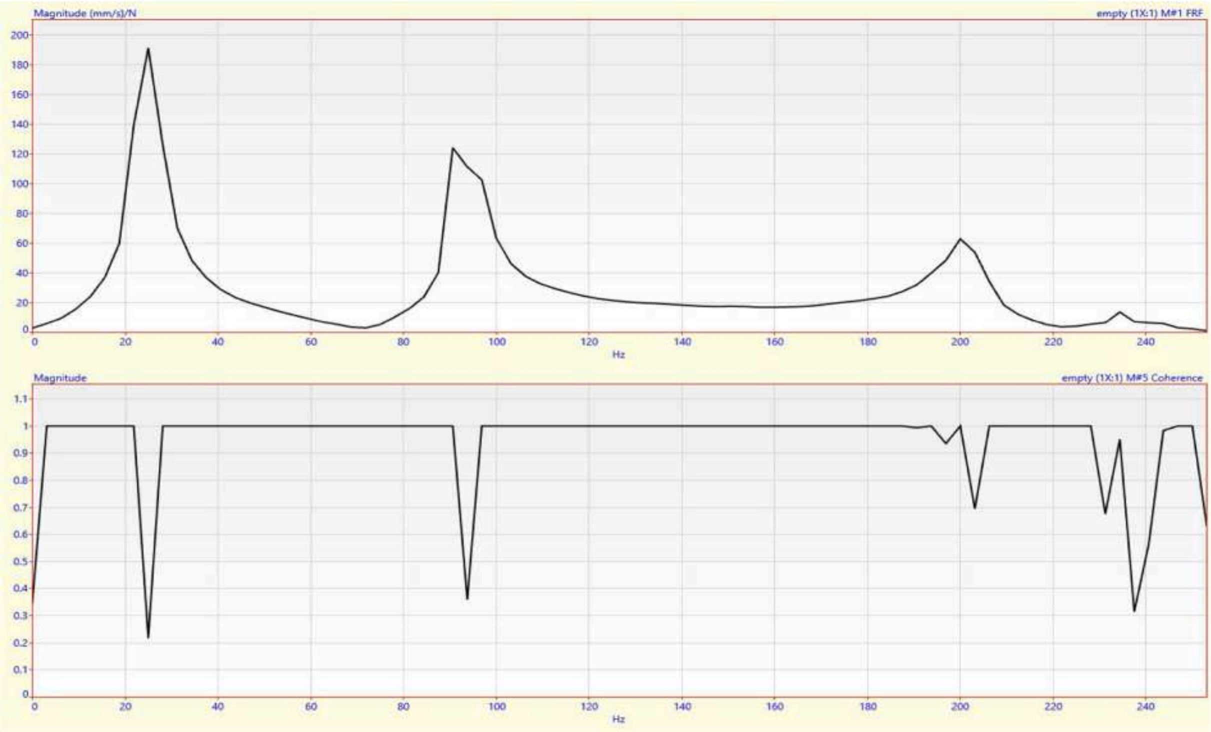

Fig. 5. Frequency response plot from EMA of the empty copper tube.

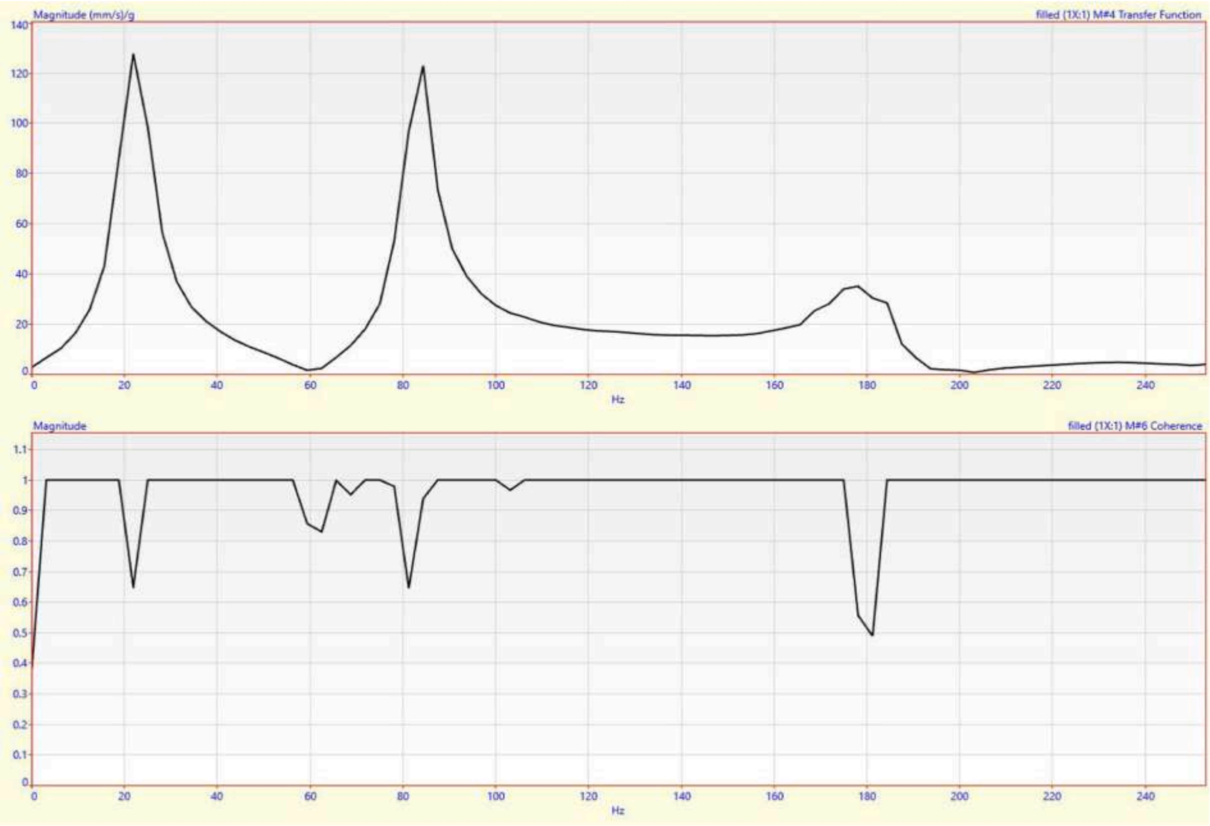

Fig. 6. Frequency response plots from EMA of water filled copper tube.

As observed in Fig. 8, the highest reduction in amplitude of vibration happens for the highest pitch length of 1000 mm. This is because, when the wire is wound as a single turn around the entire length of the tube, the stiffness addition happens along the entire length of the tube and the amplitude of vibration reduces significantly. As the copper wire length is constant, when the pitch length is decreased, length of the wire wound

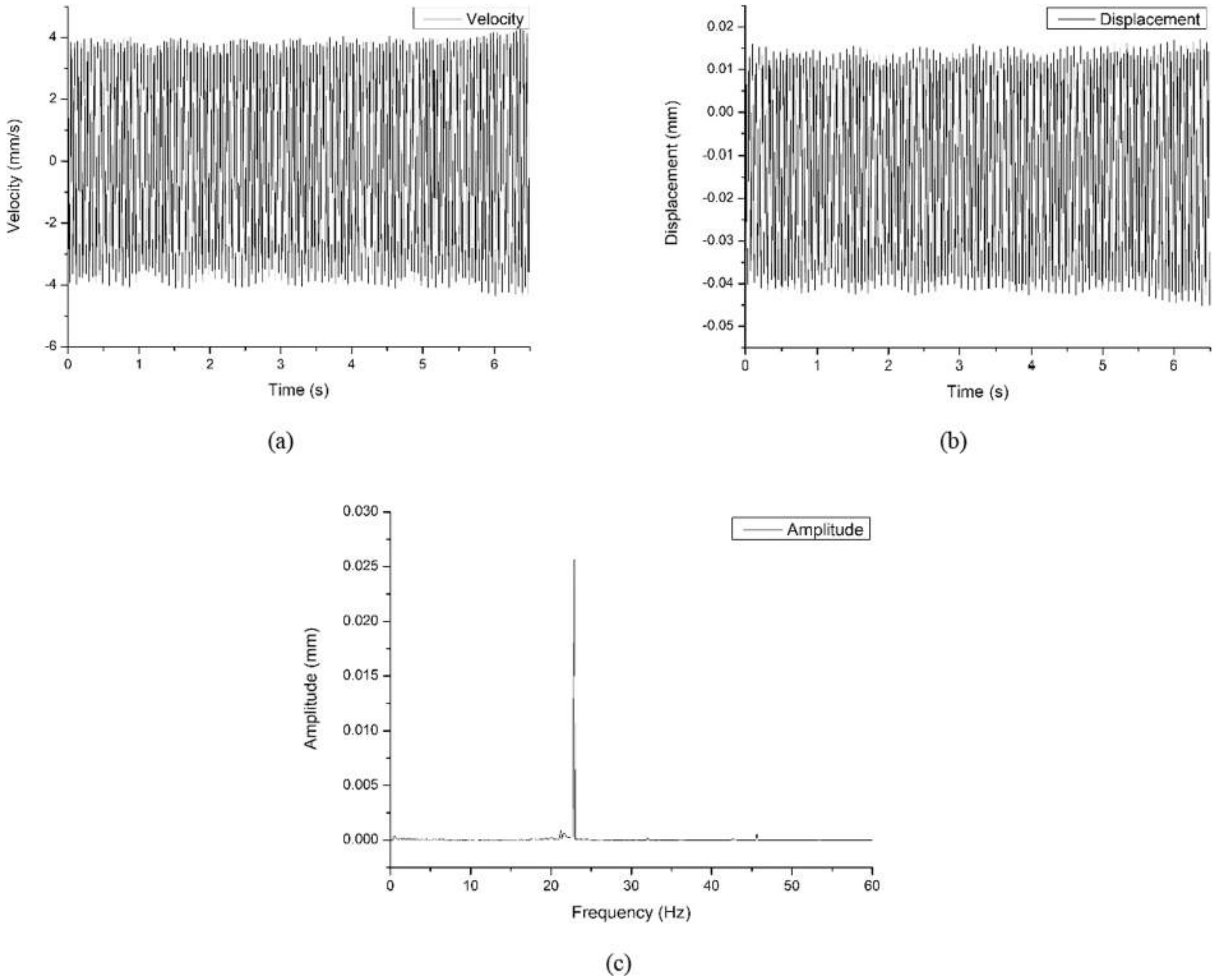

Fig. 7. (a) Time response in the form of velocity of vibration measured by LDV, (b) Displacement calculated by integrating the captured response and (c) Frequency spectrum of the copper tube conveying a fluid of velocity 19.1 cm/s at a pulse rate of 22.8 Hz.

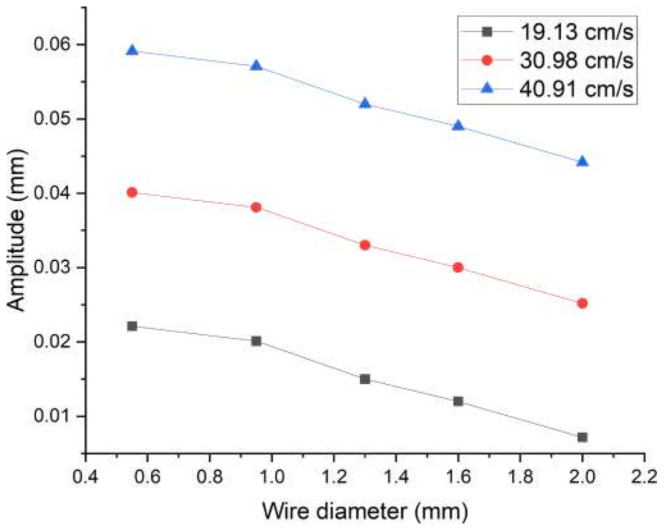

Fig. 8. Vibration amplitudes of the tube for different wires for a pitch length of 100 cm.

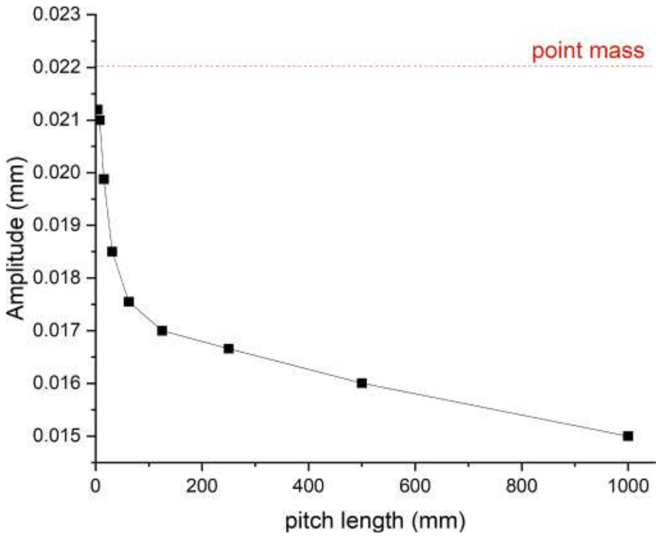

Fig. 9. Amplitude of vibration of the tube for a 12.3 g, 1035 mm wire for different pitch length.

section of the tube also is decreased. This is evident from Fig. 4. As the stiffness addition happens only at the wire wound length, the reduction in the amplitude of vibration reduces compared to a fully wound tube. When the same mass as that of the wire is added on the centre of the tube as a point mass, the contribution towards stiffness addition is less compared to wire winding. This results in point mass having the least amplitude reduction of vibration compared to the wire winding.

Addition of the same amount of mass in different manner brings out different outputs which points at the difference in stiffness addition for each case. This points towards an easy method for controlling the amplitude of vibration at desired level using different wire winding configurations.

However, this may be considered as a preliminary study and further detailed tests may be conducted to deeply analyse these results. Modal parameters such as natural frequency, damping and mode shapes should be analysed in extension to strengthen these findings.

5. Conclusion

In this study, the development of an experimental method to analyse the vibrational behaviour of tubes conveying a pulsatile fluid is discussed. The influence of wire winding on the dynamics of a water conveying copper tube was successfully captured using the experimental set up. The study brings out significant findings:

- Amplitude of vibration of the tube was observed to vary upon changes in the wire winding configurations.
- Addition of the same amount of mass in different wire winding configurations resulted in different vibration outputs.
- The analysis of the variations in the amplitude of vibration of the tube brings out the phenomenon of stiffness addition proportional to wire winding configurations.

This study suggests a possible vibration amplitude control method using wire windings. Wire windings in various configurations can be applied on fluid conveying tubes to control vibration amplitudes at desired levels. This method can be further studied and applied to similar cases to control vibrations in different fields such as fluid transportation pipelines, hydraulic piping, offshore/marine piping, and to design nuclear fuel rods, fins of boiler tubes, coiled heats exchangers used in the power, chemical, pharmaceutical and food industries, etc.

CRediT authorship contribution statement

K. Sayooj: Investigation, Data curation, Writing – original draft, Visualization. **R. Kamal Krishna:** Conceptualization, Methodology. **M. Unnikrishnan:** Resources, Project administration, Writing – review & editing, Validation, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Sayooj K reports financial support was provided by Centre for Engineering Research and Development, APJ Abdul Kalam technological University.].

Data availability

Data will be made available on request.

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