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ORIGINAL CONTRIBUTION

Dynamic Behaviour of Flexible Silicone Tube Subjected to Pulsatile Flow

R. Kamal Krishna[1] · Amal G. Nath[2] · S. Anoop Kumar[2] · M. Unnikrishnan[1] · Jayaraj Kochupillai[3]

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Abstract Flexible Silicone tubes possess superior qualities such as higher corrosion resistance, purity, strength, and inertness compared to other flexible tubes. Hence, these tubes own broad applicability in medical applications as well as other industrial applications. An unsteady flow through the flexible tube can induce severe internal excitation, which results in the flow-induced vibrations. Such vibrations at resonance can cause severe damage to the structure. Concerning the flexible tubes used in sophisticated medical applications, it is imperative to eliminate the structural vibrations, as far as possible. The present study examines the dynamics of the silicone tube under internal excitation due to pulsatile flow. It includes the investigation of the effect of pre-stretch and mean flow velocity on the dynamic behaviour of flexible tube by conducting parametric studies using the operational modal analysis technique. The influence of the mean flow velocity in the flexible tube is a proportional variation in the magnitude of vibration concerning fluid flow rate. An advance in pre-stretch causes a decrease in sagging, and the tube tends to retrieve its original circular cylindrical shape. Owing to this, when the tube is excited due to internal pulsation, the difference between the magnitude of vibration in the horizontal and vertical plane at resonance condition reduces, and the natural frequencies at different planes nearly become equal at higher pre-stretch, where sagging is negligible. The study reveals that for flexible tubes, the tube vibration always stabilizes in an arbitrary plane under excitation due to pulsation. This investigation exhibits that impact hammer excitation is better than constrained external excitation to find the fundamental frequencies of the flexible tube conveying fluid.

Keywords Pulsatile flow · Excitation · Flexible tube · Pre-stretch · Fundamental frequency · Sagging · Beat

Introduction

Flexible fluid conveying tubes find numerous applications in the areas of gaseous, liquid as well as multi-phase fluid transfer systems. Industries and medical fields are two of the major fields of applications of flexible tubes. Silicone tube is well known for its purity and inertness, which makes it well suited for medical applications. It owns superior strength, flexibility and corrosion resistance owing to which the silicone tubes offer long life. Its ease of processability makes it a prominent name among flexible tubes. Due to these reasons, silicone tubes find applications in pharmaceutical as well as nutrient conveying tubes, peristaltic pumps, catheters, and flow metres. Since the application includes intricate fields like medical equipment, it is necessary to be careful to avoid any kind of malfunctioning due to flow-induced vibration. Fluid–structure interaction (FSI) resulting from the transfer of energy from and to the fluid can cause vibrations which can be severe. Unlike rigid metallic tubes, flexible tubes like silicone tubes are prone to severe flow-induced vibrations as it actively participates in fluid–structure interaction.

✉ Jayaraj Kochupillai
jayaraj@cet.ac.in

[1] Advanced Dynamics and Control Lab, College of Engineering, Trivandrum, India

[2] Sree Chitra Thirunal College of Engineering, Trivandrum, India

[3] Mechanical Engineering Department, Government Engineering College, Barton Hill, Trivandrum, India

Even in the absence of external excitations, internal flow variations, and imperfections in pipe geometry or material homogeneity can results in flow-induced vibrations in tubes conveying fluid. Fluid–structure interaction and flow-induced vibrations are of prime importance in the dynamics of fluid conveying pipelines as the negligence of internal excitations due to flow pulsations can result in damage and failure. Hence, the dynamics of fluid conveying tubes is always one of the areas of attention.

Internal fluid flow is a vital aspect in the study of the dynamic behaviour of fluid conveying tubes and flow-induced vibrations. The investigation of fundamental frequencies of tube conveying fluid helps to identify the safe operating frequencies of tubes and to design its supports. If the fundamental frequency of the tube and the internal pulse frequency are matching, resonance may occur, and it can cause instability, which can result in fatigue, leakage, and failures. Operational modal analysis (OMA) gives the modal properties of a structure based on vibration data of structure at operating conditions [1]. Fundamental frequencies and mode shapes are the modal properties of a structure. Operational deflection shape (ODS) gives additional insight into noise or vibration problems that individual measurements alone do not since it provides deflection of a structure at a specific frequency and the amplitude and phase of vibration of the system.

Vast studies have been conducted on flow through tubes in the past years. Experimental studies on the dynamics of fluid conveying flexible tubes are not numerous even though theoretical and numerical studies are many. Traditional analytical studies on this area are generally simplified as it neglects the FSI part. Initially, several studies addressed only the effect on fluid flow on the pipe but ignored the reverse case, i.e. the impact of pipe motion on fluid flow. However, the importance of FSI was brought to light by numerous works later and is more significant on flexible tubes. The effect of transverse, axial, and radial vibrations in steady as well as unsteady flow conditions are incorporated in the continuity equation [2–4]. The studies disclose the influence of flow velocity on fluid pressure. Later on, analytical and experimental studies on flexible tubes revealed that the support condition, tube material, and tube geometry play a vital role in the tube dynamics. Most of these studies were limited to steady flow conditions and the effects of different parameters like the initial stretch, pressure as well as flow velocity on the critical flow velocity and natural frequency [5–8]. Various studies were published later on, which reveal the significance of FSI on fluid conveying tubes [9–11]. These studies are mainly concentrating steady flow, and hence, the effect of unsteady flow like varying pressure and varying velocity on dynamics is not adequately investigated experimentally.

Nevertheless, it is an area of prime importance as the variation in velocity or pressure can cause internal excitation and thereby affect tube dynamics. Studies incorporating pulsatile flow and varying velocity flow are not numerous. The analytical study on harmonically varying flow velocity revealed an error factor when compared to the steady flow and also a rise in instability [4]. The study of pulsatile flow with harmonic perturbation showed that the amplitude of the oscillating component and flow velocity is proportional [12]. In some cases like cantilever support conditions, the addition of the pulsatile component sometimes resulted in the stabilization of the tube [13]. A numerical study considering unsteady flow in a fluid conveying tube revealed that a rise in pulsation frequency caused an increase in longitudinal vibration [14]. Pulsation of flow in the tube affected the accuracy of Coriolis flow metre. When pulse frequency or any of its harmonics coincided with fundamental frequencies, the measurement accuracies in dynamic characteristics degrade [15]. Recent studies were concentrating on flexible tubes subjected to external excitation. One of the studies analyses the effect of stretch rate and flow velocity on the damping ratio in a stretched rubber tube subjected to external excitation. The damping ratio increased with an increment in the flow velocity and a reduction in stretch rate [16].

The experimental investigation on silicone tube conveying fluid unveiled the dynamic characteristics of the tube under the sagged condition when subjected to constrained external excitation. The beat phenomenon was identified in the *X*–*Y* and *X*–*Z* plane when the tube was under low pre-stretch. Increasing pre-stretch decreased the effect indicating the impact of sagging of the tube. The numerical results exhibited a good correlation. The effect of pre-stretch, flow rate, and length on the behaviour of silicone tubes were also investigated [17]. A review of the literature reveals that most of the researchers give more importance to the external excitation of fluid conveying tubes only. However, internal excitation of tubes needs thorough investigation as it can cause flow-induced vibrations in operating conditions, which is not negligible.

The thorough literature reveals that even though numerous works on flow through flexible tubes are available, experimental studies accounting excitation due to pulsatile flow in flexible tubes and the resulting flow-induced vibrations are very rare. Further, the studies related to the sagging of flexible tube, tube cross-sectional shape change, and the effect these parameters on the dynamics are scarce in the literature. The current work stands out from similar works such as [16, 17] by addressing the internal excitation due to pulsatile flow and hence induced flow-induced vibrations. The paper describes an experimental study on the dynamic behaviour of the flexible silicone tube subjected to pulsatile flow, including the stretch, sagging effect, and mean flow velocity.

Theory

Dynamics of Pipes Conveying Steady Fluid

The governing equation for fluid conveying vertically placed slender pipe is presented in Paidoussis [18] as follows. The fluid element shown in Fig. 1a carries gravity forces, reaction forces of the pipe, pipe shear force, and pressure forces acting on fluid element due to the frictional losses. Figure 1b depicts the moment and force balance of the corresponding element of the pipe

The general equation of motion based on beam theory if the effect of gravity is not negligible, plug flow model for fluid and assuming small perturbations in the velocity of flow along the radial direction is given by,

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

where L is the length of tube in m, S is the Interior perimeter of the tube in m, A is the inside area of the tube in m^2, m is the linear density of pipe in kg/m, E is the elastic modulus in MPa, I is the moment of inertia in m^4, EI is the flexural rigidity in MPa m^4, E^* is the coefficient of viscoelastic damping of pipe in MPa s, c is the coefficient of viscous damping in Ns/m, P is the pressure in Pa, υ is the Poison ratio, T is the longitudinal tension of tube in N, q is the wall shear stress in $\mathrm{N/m}^2$, M_b is the bending moment, w is the lateral deflection of tube, M is the linear density of the fluid in kg/m, and U is the axial fluid flow rate in m/s

If the effect of pre-tensioning, damping (energy dissipation), internal fluid pressurization, and sagging (gravity) are absent or neglected, Eq. (1) simplifies to

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

The flexural restoring force, the centrifugal force, the Coriolis force, and the inertial force, respectively, are the four terms in Eq. (2).

For flexible tubes subjected to pulsatile flow, the internal fluid pressurization is dominant, and hence, the effects of pressurization need to be included in the analysis. It is evident from Eq. (1) that pressurization causes imbalance to the whole system. Also, the assumption that velocity remains constant is not applicable. So there is a need for the experimental study concentrating on an unsteady flow such as pulsatile flow through flexible tubes.

Experimental Setup

Test Facility

The test facility comprises of a test field, measurement and control devices, rotary valve, and storage tanks as shown in Figs. 2a, b and 3. The test section consists of a clamped–clamped silicone tube placed horizontally. The length of the test section is 36 cm, with the inner and outer diameters of the tube being 6 mm and 9 mm, respectively. Two interconnected overhead water tanks maintain a constant head over the test section. The water storage tank gains a total head of 1.92 m, which is maintained continuously

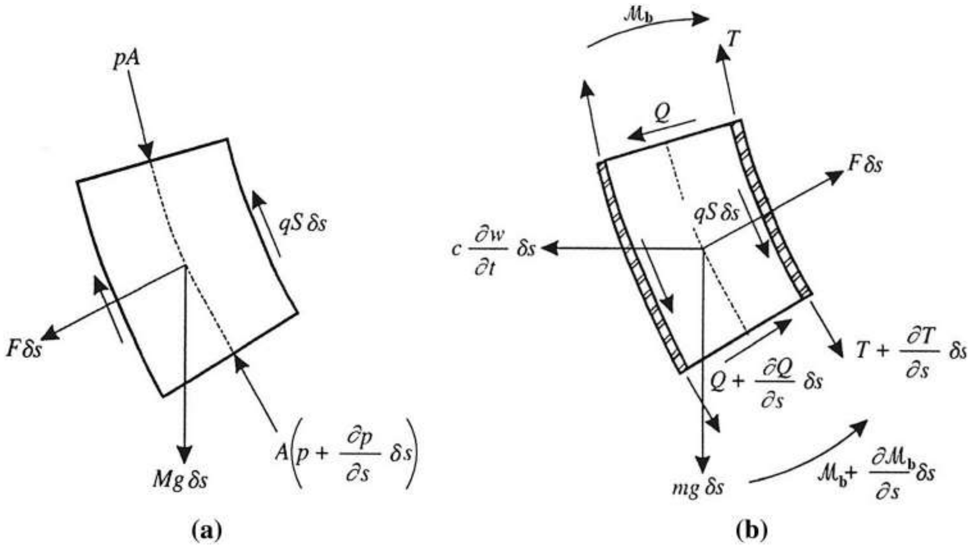


Fig. 1 **a** Force balance of a fluid element δ_s [18], **b** moment and force balance of the corresponding element of the pipe [18]

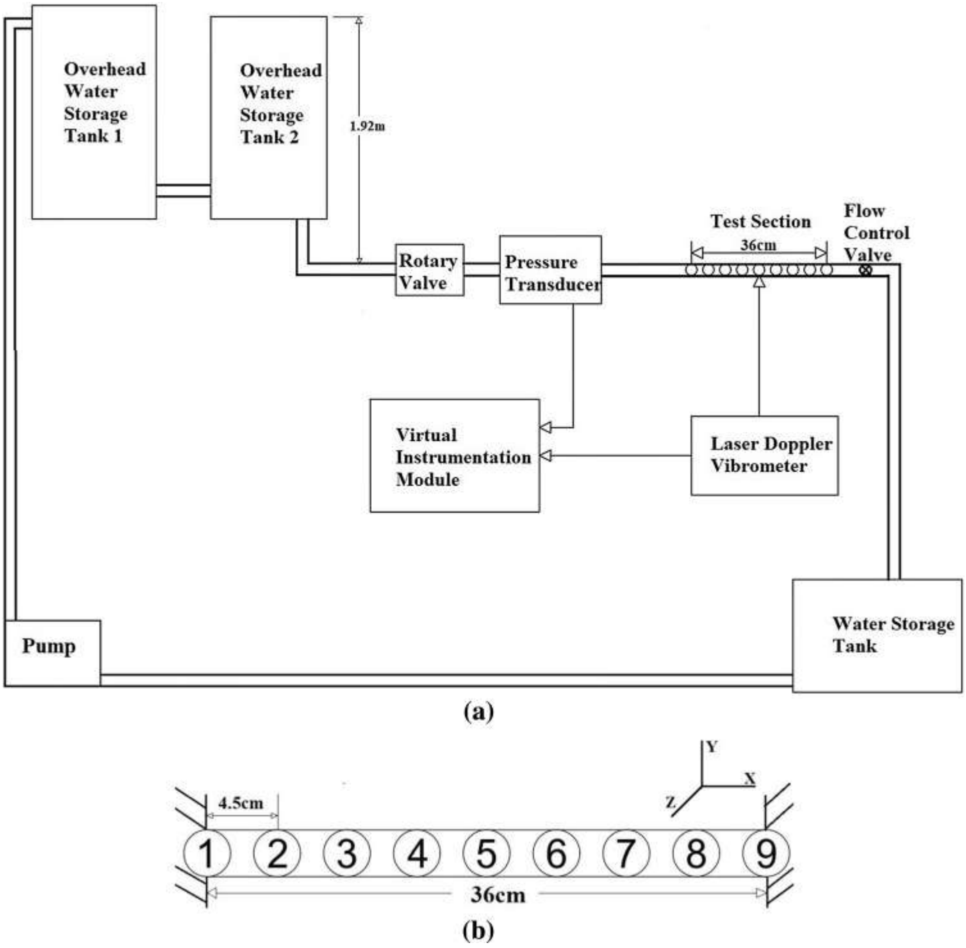


Fig. 2 **a** Layout of the test setup and **b** test section clamped at 1&9 with reflective tapes adhered from points 2 to 8 equidistantly

using a float valve mechanism. A pump refills the reservoir tank from the collecting tank. An in-house designed rotary valve that can rotate 360° is placed on the path before the fluid reaches the test section. The valve opens and closes twice on one full rotation. The valve works with the help of a variable frequency drive (VFD) controlled motor.

A mechanical coupling connects the shaft and rotary valve. The motor and the valve coupled with it rotate at the same frequency when VFD is set to the required frequency. The pulse frequency, i.e. the frequency at which the pulses generates, is twice the VFD set frequency since the valve opens and closes twice on one full rotation. The rotation of the valve induces a velocity change in the flow as the flow varies from no flow condition to a maximum flow condition. The difference in fluid velocity makes the flow pulsatile in nature, and this pulsatile flow causes excitation of the tube. The maximum flow velocity when the valve is fully open is 1.7 m/s. The mean flow velocity is found by measuring the flow rate through the test section.

Pressure transducer monitors the pressure change and pulse frequency in the test section. The laser Doppler vibrometer acquires the dynamic response of the tube. Dynamic signal analysers and LabVIEW Signal Express 2011 post-process and analyse the received signals. Major equipment used for the experiment and its details are shown in Table 1.

Experimental Method

The flexible silicone tube is kept horizontal with a minimum pre-stretch, and the tube is clamped correctly at the ends using two clamps. The test section consists of eight equal divisions with the endpoints 1, and 9 are fixed (depicted in Fig. 2b). The reflective tapes pasted at the seven intermediate points of the test section help in the reflection of the laser beam. Laser Doppler vibrometer is used to obtain the dynamic response from these seven points. Out of the two clamps, one clamp is capable of moving axially for applying pre-stretch in the tube. Pre-stretching is measured using a pointer attached in the clamp. A scale is attached to the frame to observe the length of pre-stretch. Pre-stretch is generally expressed as a percentage increase in the length of the tube concerning the original length of the tube. Three pre-stretch conditions are selected for analysis—10%, 15%, and 20%, respectively.

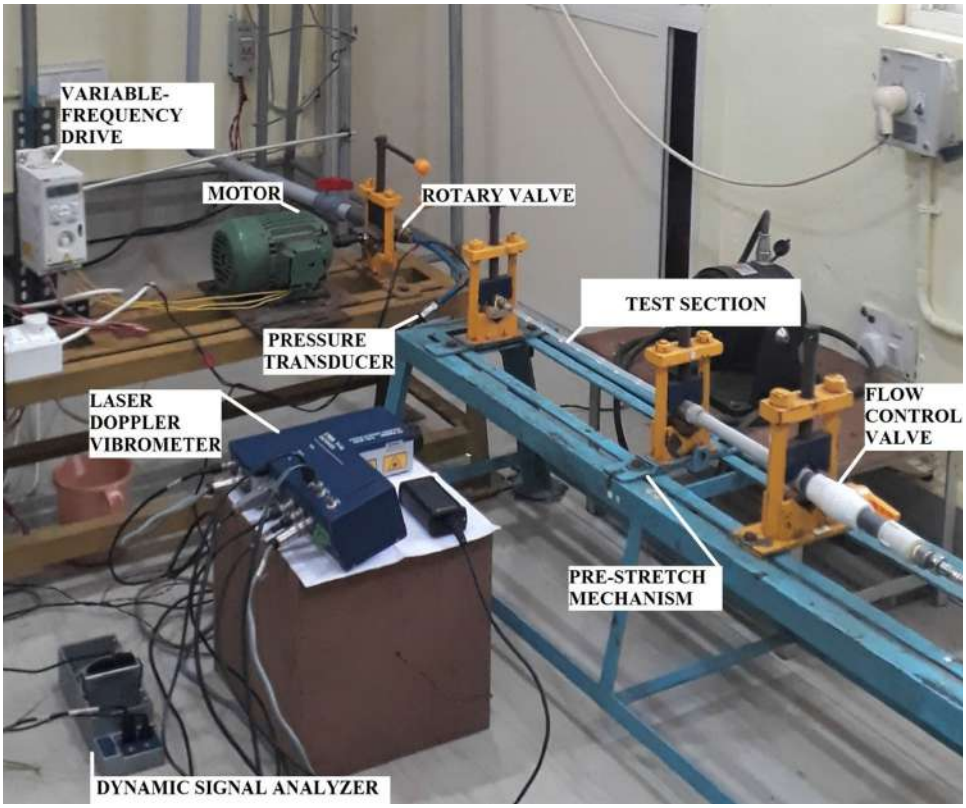


Fig. 3 Test setup

Table 1 Major equipment used and its details

Equipment	Make and model
Pressure transducer	Baumer CTX 333b220 [19]
Laser Doppler vibrometer	Polytec IVS400 [20]
Dynamic signal analysers	NI-USB 4431, NI CDAQ 9278 and 9205
Variable frequency drive	ABB ACS310

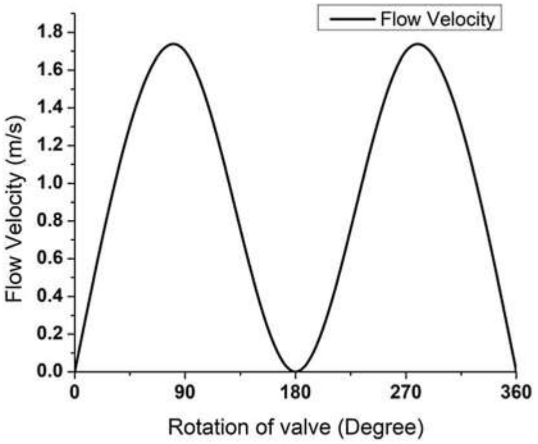


Fig. 4 Flow velocity corresponding to the rotation of the rotary valve

The rotary valve is a simple on–off valve which varies the velocity of fluid entering the silicone tube. Thus, the rotary valve induces pulsatile flow in the test specimen. Figures 4 and 5a, b represent the velocity and pressure variations inside the tube, respectively. When the valve closes and flow arrests, no volume of water exists in the region ahead, and hence, a compressive load generates in the tube. The fluid inertia due to valve closure and compressive load variation creates a negative pressure in the test section. On reopening, the pressure rises back, and this cycle continuously occurs, which results in the pulsatile flow of fluid. The maximum pressure of pulsatile flow is always below the pressure provided by the water head. In the case of conventional metallic tubes, the expansion and compression due to perturbation or pulsation of fluid flow are not severe due to higher strength of tubes. At the same time, the event of expansion and contraction of the tube along the radial direction is significant for flexible tubes, which generally leads to flow-induced vibrations.

The impact hammer helps in exciting the fluid-filled tube externally to find the fundamental frequency of the flexible tube under the no flow condition for each pre-stretching. The tube when subjected to impact hammer excitation vibrates initially in the plane of excitation, but then stabilizes in the arbitrary plane in which the tube

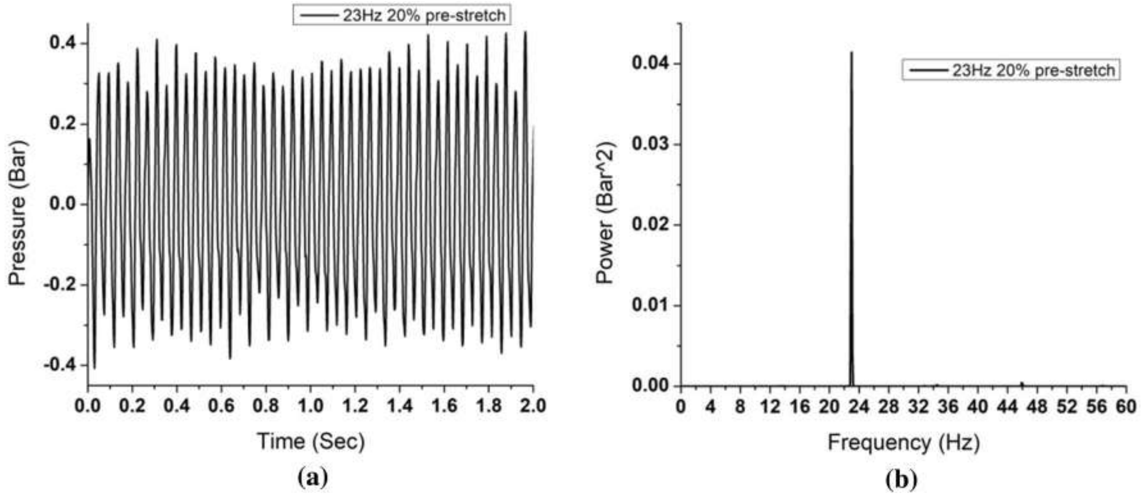


Fig. 5 **a** Pressure plot obtained from pressure transducer at 23 Hz pulse frequency at 20% pre-stretch and **b** power spectrum obtained from pressure transducer at 23 Hz pulse frequency at 20% pre-stretch

vibrates at the fundamental frequency. The fundamental frequency of the tube is identified by exciting it at its centre point (named as point number 5) using impact hammer. The inverse ODS and its fast Fourier transform (FFT) help to identify the fundamental frequency, which is similar to the OMA analysis.

A set of experiments are done by varying the pulse frequencies in a selected range. For each pre-stretch, the range is chosen (Table 2), and analyses are repeated for ensuring repeatability. Resonance conditions are identified in each pre-stretch condition when first fundamental frequency matches the pulse frequency. OMA is done at each pulse frequency using laser Doppler vibrometer, dynamic signal analysers, and LABVIEW Signal Express 2011 software.

The necessary parameters for data acquisition are taken from [21] and are as follows. On the time domain, the number of samples is taken as 8192, and time resolution is 0.0008. The window type used is the Hanning window. On the frequency domain, the number of samples is taken as 4096, the number of averages is 50, and the frequency resolution is 0.153.

Table 2 Frequency range

Pre-stretch (%)	Frequency range (Hz)
10	14–22
15	14–25
20	17–26

Result and Discussions

The impact hammer helps to determine the fundamental frequencies of the fluid conveying flexible tube. Table 3 represents the first fundamental frequencies (first bending mode of vibration) under each pre-stretch condition. Frequency plots depicting the first fundamental frequencies are shown in Fig. 6a–c. The mode shapes are plotted using MEscope VES software from the response obtained from laser Doppler vibrometer and shown in Fig. 6d, e. If one uses pulsation of the fluid to excite the flexible tube at its fundamental frequency, the tube vibrates in the arbitrary plane that matches with the plane obtained during impact hammer excitation. If an exciter excites the sagged tube, one gets different frequencies for vertical and horizontal direction [17].

Comparative Study

Constrained external excitation is one of the most common techniques used to find the fundamental frequencies of

Table 3 First fundamental frequencies obtained via impact hammer excitation

Tube length 36 cm		
Pre-stretch (%)	First fundamental frequency	
	X–Z plane (Hz)	*X–Y* plane (Hz)
10	18	18
15	19.4	19.4
20	20.6	20.6

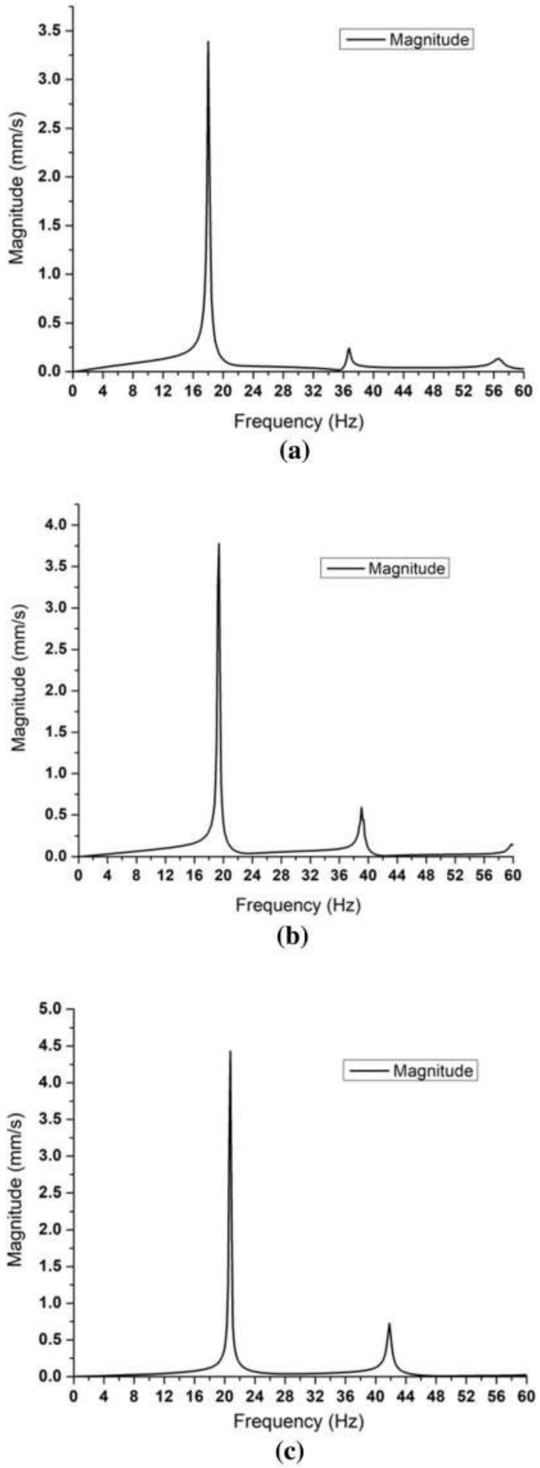


Fig. 6 **a** Frequency plot showing the first fundamental frequencies obtained by impact hammer excitation under 10% pre-stretch, **b** frequency plot showing the first fundamental frequencies obtained by impact hammer excitation under 15% pre-stretch, **c** frequency plot showing the first fundamental frequencies obtained by impact hammer excitation under 20% pre-stretch, **d** mode shape corresponding to first fundamental frequency, and **e** mode shape corresponding to second fundamental frequency

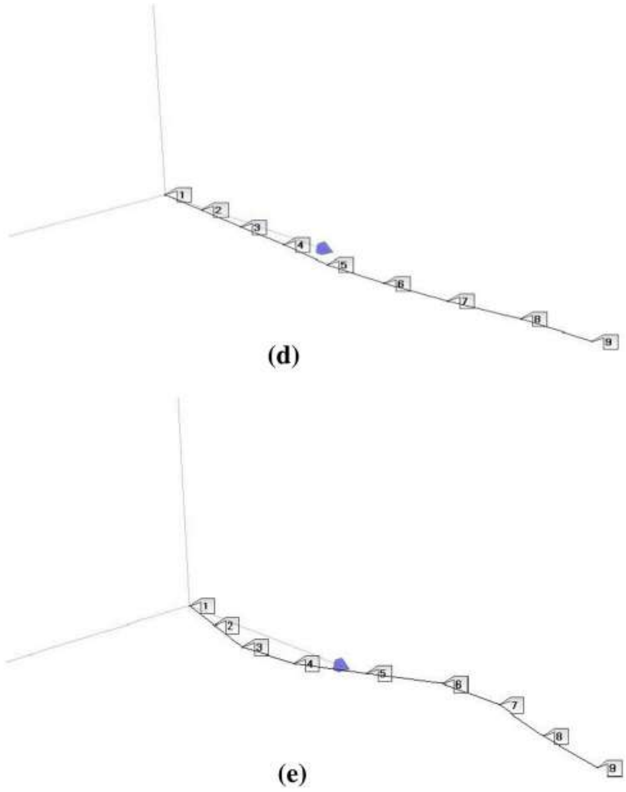


Fig. 6 continued

tubes, especially for isotropic metallic tubes. Table 4 represents the first fundamental frequencies of silicone tube (length—36 cm, inner diameter—6 mm, outer diameter—9 mm) in *X*–*Z* and the *X*–*Y* plane as reported in [17] using the constrained excitation method under fluid-filled no flow condition for 10%, 15%, and 20% pre-stretches, respectively. The study identifies the beat phenomenon due to sagging in flexible tubes conveying fluid and observed that increasing the tube pre-stretching reduces the beat frequency.

In the current study, the dynamic characteristics of the flexible tube with internal excitation due to pulsation of flow is addressed and investigated. Here, for the flexible tubes conveying fluid with internal excitation due to the pulsation of flow, the beat phenomenon caused by sagging is not found. But when the flexible tube is subjected to constrained external excitation, the tube deforms and tries to vibrate in the plane of excitation. Hence, the fundamental frequency is different for various planes of vibration. The fundamental natural frequency and external excitation of the flexible tube create the beat phenomenon. But under excitation due to the pulsation of flow, the tube is free to vibrate in a particular arbitrary plane and stabilizes. Hence, the tube has a single first fundamental frequency, and vibration dominates in that plane of vibration with this single fundamental frequency. So for the flexible

Table 4 First fundamental frequencies obtained via constrained external excitation

Tube length 36 cm		
Pre-stretch (%)	First fundamental frequency (Hz) of the tube with no fluid flow	
	X–Z plane	*X–Y* plane
10	15.9	21.3
15	19.2	24.9
20	20.3	20.4

tubes with internal excitation, the beat phenomenon due to sagging is absent.

As the flexible tube is pre-stretched to 20% of its initial length, both the fundamental frequencies obtained using constrained external excitation and impact hammer excitation are similar (Tables 3, 4). This investigation implies that when pre-stretch is enough to nullify the sagging effect, fundamental frequencies do not vary irrespective of the type of excitation. However, under low pre-stretch conditions, the impact of sagging causes a notable difference in the dynamic behaviour of the silicone tube. The study depicts that silicone tube under sagged condition behaves differently when subjected to external excitation and excitation due to the pulsation of flow. So the nature of excitation plays a vital role in tube dynamics. Also, the paper reveals that for flexible tubes under sagged condition, impact hammer excitation method is more suitable for finding fundamental frequencies.

Parametric Study

Experiments on 36-cm-long silicone tube are carried out by varying the pulse frequencies on all pre-stretch conditions. The frequency range is chosen such that it includes the fundamental frequency obtained by impact hammer excitation (Table 3) and constrained external excitation (Table 4). Resonance condition is observed when the pulse frequency (f_p) matches with first fundamental frequency (f_1) obtained from impact hammer excitation under every pre-stretch condition. The dominant mode of tube vibration is the first bending mode of vibration as the comparable fundamental frequency corresponds to the first bending mode. Figures 7a, b, 8a, b and 9a, b represent the frequency plots under varying pulse frequencies of 10%, 15%, and 20% pre-stretch, respectively. The magnitude of vibrations at resonance is obtained ten times the magnitude compared to other pulse frequencies in the vicinity. Peaks of magnitude are present at pulse frequency as well as its harmonics (nf_p where $n = 1, 2, 3 \ldots$) as explained in [4]. Apart from resonance condition where $f_1 = f_p$, small peaks of magnitude are visible at fundamental frequencies as well as at the half harmonics of pulse frequencies ($\frac{xf_p}{2}$ where $x = 1, 3, 5, \ldots$). These frequencies account for the rotation of the valve at a frequency of half the pulse frequency. The magnitude of vibration for all other resonance conditions compared to resonance happed at $f_1 = f_p$ is less. For the events other than $f_1 = f_p$, energy transfer is observed more at higher harmonics of pulse frequency than at induced pulse frequency, but of very less magnitude when compared to resonance condition. It is noted that the tube may not tend to vibrate and transfer energy more at the induced

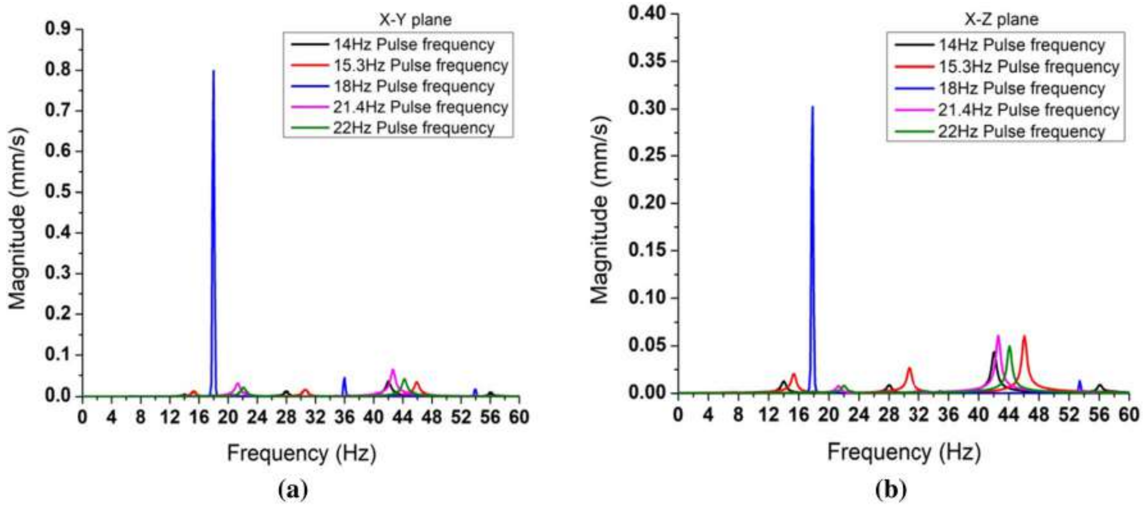


Fig. 7 **a** Frequency plot of 10% pre-stretched silicone tube at different pulse frequencies in the *X–Y* plane and **b** frequency plot of 10% pre-stretched silicone tube at different pulse frequencies in the *X–Z* plane

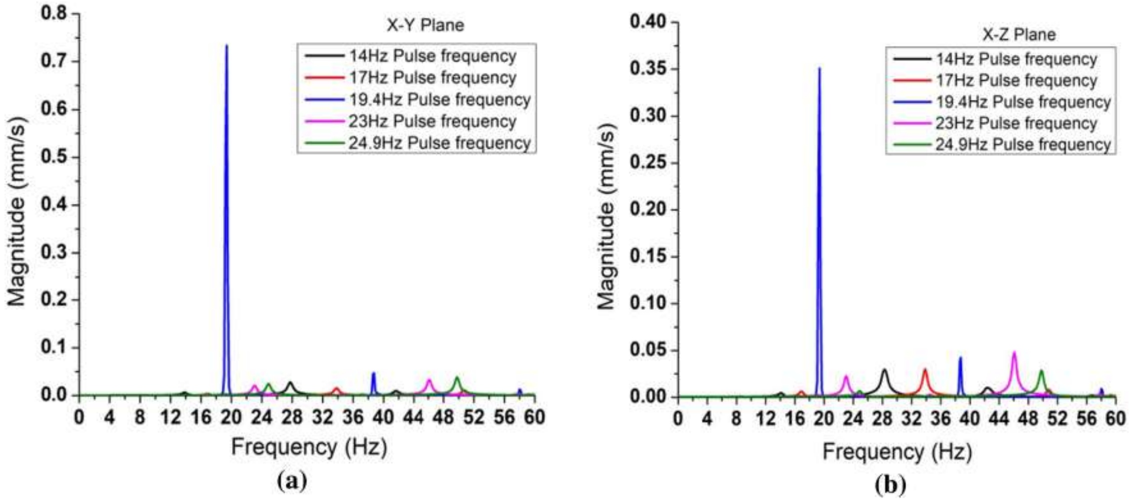


Fig. 8 **a** Frequency plot of 15% pre-stretched silicone tube at different pulse frequencies in the *X–Y* plane and **b** frequency plot of 15% pre-stretched silicone tube at different pulse frequencies in the *X–Z* plane

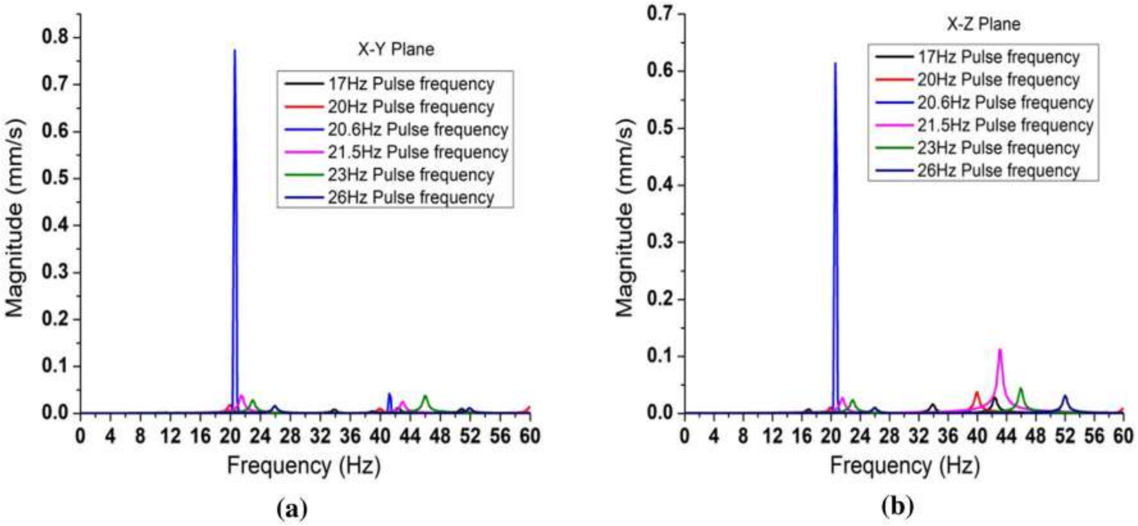


Fig. 9 **a** Frequency plot of 20% pre-stretched silicone tube at different pulse frequencies in the *X–Y* plane and **b** frequency plot of 20% pre-stretched silicone tube at different pulse frequencies in the *X–Z* plane

pulse, rather more energy transfer can be at higher harmonic frequencies. This effect may be accounted due to the perturbation of fluid, fluid–structure interaction, and self-stabilization nature of the tube. In the case of excitation, due to the pulsation of flow, resonance condition where $f_1 = f_p$ is salient and hence this particular frequency is focussed in further studies.

Effect of Varying Pre-stretch

A silicone tube of 36 cm initial length is analysed under various pre-stretch. In low pre-stretch conditions, the tube is in sagged condition. The tube is excited in resonance condition where $f_1 = f_p$ on each pre-stretch. The magnitude of vibration in the *X–Z* and *X–Y* plane along with their difference is represented in Fig. 10a, b and Table 5. As reported in many of the earlier works on flexible tubes, natural frequency increases corresponding to the increase in pre-stretch.

The magnitude of vibration in the *X–Y* plane seems to remain nearly the same in all conditions. But the vibration in the *X–Z* plane tends to increase when we increase the pre-stretch. As a result, the difference in magnitude decreases as pre-stretch is increased to 20%. The mass of the water column acting downwards acts as an added mass through the flexible tube results in the sagging of the tube.

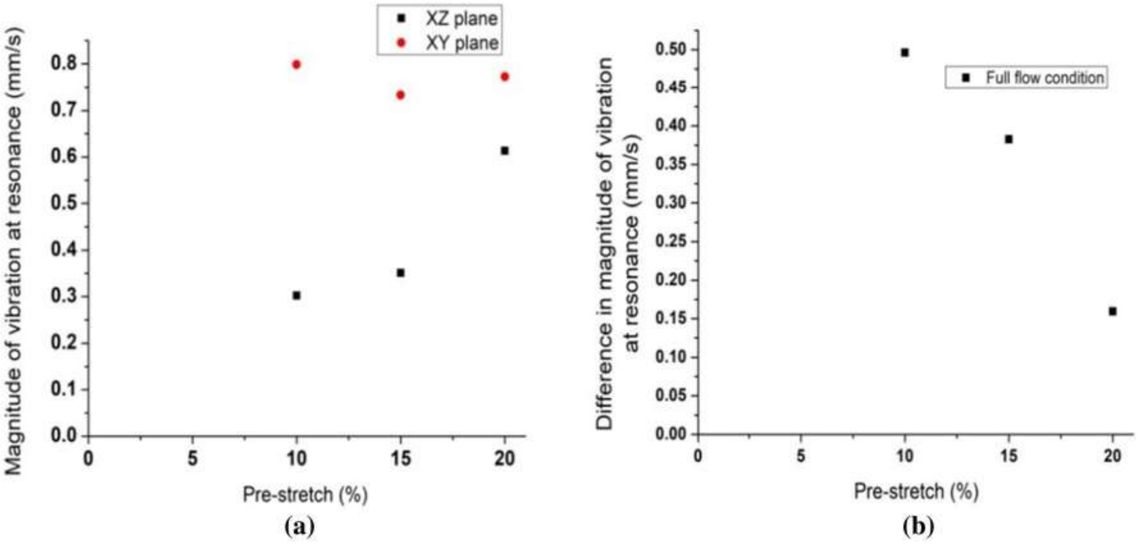


Fig. 10 **a** Magnitude of vibration at resonance in *X–Z* and *X–Y* plane versus pre-stretch and **b** difference in the magnitude of vibration at resonance in *X–Z* and *X–Y* plane versus pre-stretch

Table 5 Magnitude of vibration at resonance condition in X–Z and X–Y plane

Pre-stretch (%)	First fundamental frequency (Hz)	The magnitude of vibration (mm/s)		The difference in magnitude (mm/s)
		X–Z plane	*X–Y* plane	
10	18	0.30243	0.79866	0.49623
15	19.4	0.3508	0.73341	0.38261
20	20.8	0.61357	0.77288	0.15931

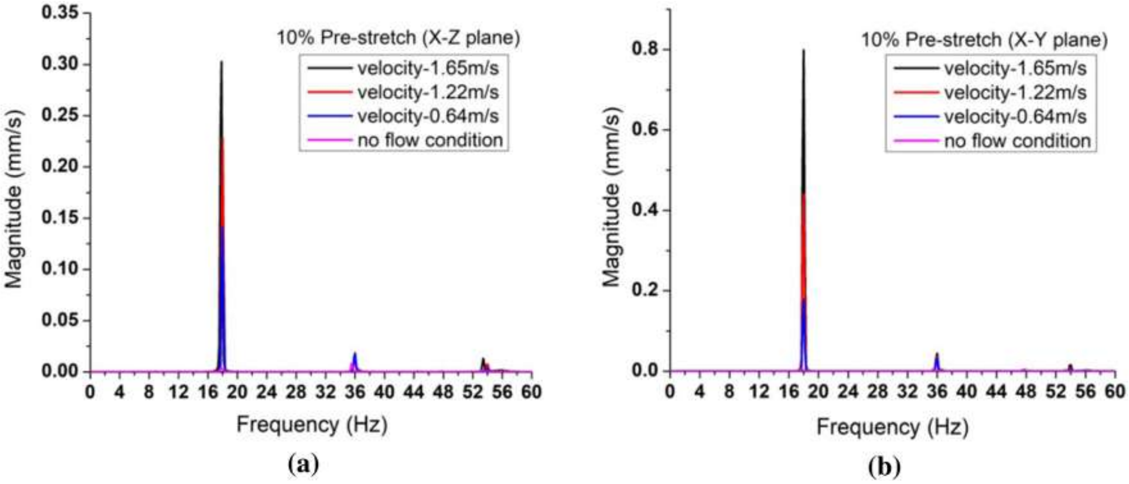
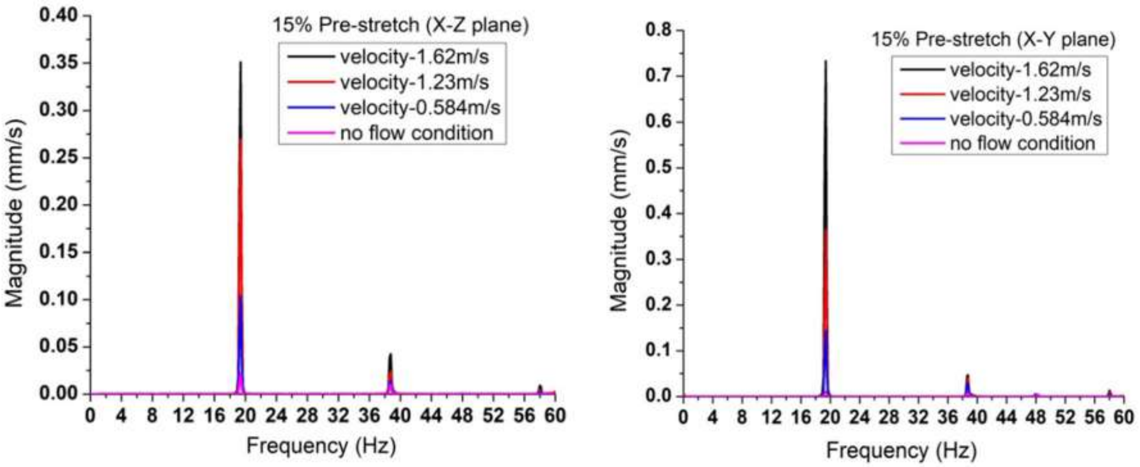


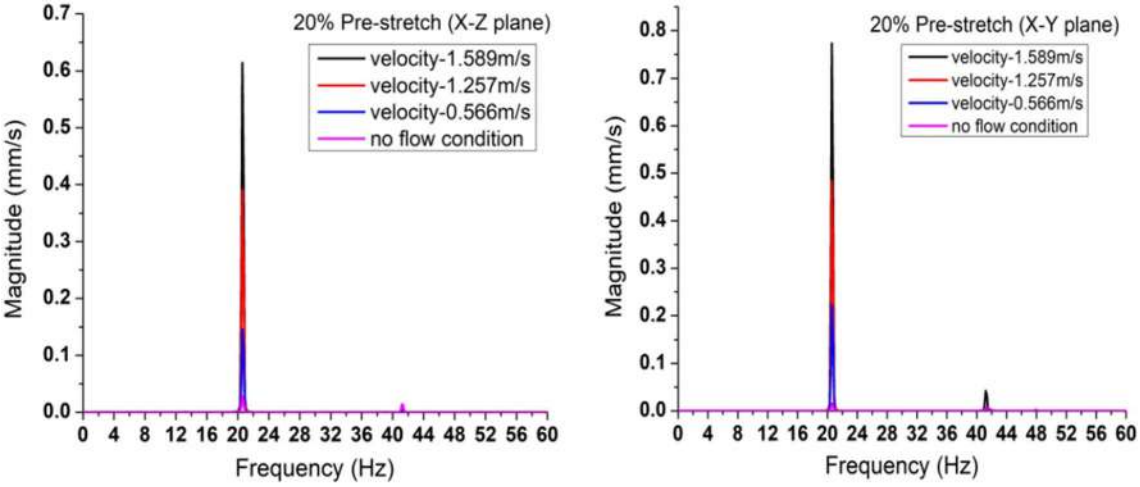
Fig. 11 **a** Frequency plot of 10% pre-stretched silicone tube at different mean flow velocities in the *X–Z* plane and **b** frequency plot of 10% pre-stretched silicone tube at different mean flow velocities in the *X–Y* plane

The shape of the tube is teardrop rather than cylindrical due to this unbalance at low pre-stretch conditions. When pre-stretch applies, tension exerts in the axial direction, which compensates for the sagging effect. The inertia of the tube in the horizontal and vertical direction changes according to the pre-stretch. The lower pre-stretches in flexible tubes



(a) (b)

Fig. 12 **a** Frequency plot of 15% pre-stretched silicone tube at different mean flow velocities in the *X–Z* plane and **b** frequency plot of 15% pre-stretched silicone tube at different mean flow velocities in the *X–Y* plane



(a) (b)

Fig. 13 **a** Frequency plot of 20% pre-stretched silicone tube at different mean flow velocities in the *X–Z* plane and **b** frequency plot of 20% pre-stretched silicone tube at different mean flow velocities in the *X–Y* plane

cause a shape change, which results in inertia change. Inertia change concerning stretch in the *X–Z* plane is much significant, and hence, the magnitude of vibration increases considerably when pre-stretch increases from 10 to 20%. But on the *X–Y* plane, the inertia change is minimal, and hence, magnitude of vibration also shows less variation. On reaching 20% pre-stretch, the tube regains its horizontal posture and circular form even though the thickness is reduced and the magnitude of vibration on both *X–Z* and *X–Y* planes tends to become uniform. The first fundamental frequency at 20% pre-stretch condition in this study and a reported study [17] are almost matching. This implies that irrespective of the type of excitation when pre-stretch is enough to nullify the sagging effect, fundamental frequencies do not vary. However, under low pre-stretch conditions, the impact of sagging causes a notable difference in the dynamic behaviour of the Silicone tube.

Effect of Varying Mean Flow Velocity

Silicone tube is excited in a resonance condition where pulse frequency and first fundamental frequency match. Mean flow velocity is varied from maximum to zero, and the corresponding behaviour change of the silicone tube is investigated. The mean flow velocity is indirectly altered by changing input fluid flow rates (using the flow control valve shown in the experimental setup) since both the quantities are proportional. The magnitude of vibration in both *X–Z* and *X–Y* planes is considered for the study. Mean flow velocities corresponding to each flow rate are obtained. Four conditions, including full flow, no flow, and two intermediate flow conditions, are chosen for the study. As reported in the earlier works [12], decreasing mean flow velocity from maximum to zero causes a reduction in the magnitude of vibration proportional to it. The flow reduction causes a decrease in the pressurization of fluid which directly reduces the amplitude of vibration. Thus, the reduction in vibration occurs proportional to flow rate reduction. Figures 11a, b, 12a, b and 13a, b depict this change in magnitude at various pre-stretch conditions in *X–Y* and *X–Z* planes.

Conclusion

This paper depicts the experimental investigation on the dynamic behaviour of a pre-stretched silicone tube subjected to pulsatile flow. Rotary valve setup induces pulsatile flow in the test section. A velocity profile similar to rectified alternating current is induced by the rotation of a rotary valve which is controlled via VFD and motor. The combined action of VFD and rotary valve causes internal excitation of the flexible tube and results in the flow-induced vibrations.

Impact hammer excitation finds to be a more suitable technique for finding the fundamental frequency of a flexible tube as the orientation of free vibration need not be along the direction of excitation in the case of excitation by the shaker. For excitation due to the pulsation of flow, the tube tends to vibrate in a particular arbitrary plane and stabilizes. Hence, beat phenomenon is not likely to occur. So it is inferred that one can use a sagged flexible tube in Coriolis flowmeter when pulsation of the fluid is responsible for excitation. In constrained external excitation, as the tube is flexible, the tube tends to vibrate in the plane of external excitation and results in a beat phenomenon. However, the paper reveals that under higher pre-stretch conditions, initial tension causes the tube to regain its circular shape and horizontal orientation. Hence, both techniques give a similar result.

Another remarkable observation of the study is the variation in magnitude in *X–Z* and *X–Y* planes under varying pre-stretch. Resonance condition where pulse frequency matched with the first fundamental frequency is chosen for further study as it is the potential condition where flow-induced vibration occurs dominantly. The magnitude of vibrations in *X–Y* and *X–Z* planes tends to become similar as pre-stretch increases. The study observes a significant increase in magnitude in the *X–Z* plane, unlike the *X–Y* plane, which accounts for the dominant inertia change in the *X–Z* plane due to shape change. But on the *X–Y* plane, inertia change is minimal. On varying the mean flow velocity by altering the inlet fluid flow rate from full flow to no flow, the magnitude of vibrations observes to diminish corresponding to the flow condition in a linear manner. This decrease in amplitude of vibration accounts for the reduction in pressurization corresponding to flow reduction.

This paper provides a basic idea and knowledge regarding the dynamic behaviour of Silicone tube conveying fluid with pulsatile flow. Future works are to be conducted concentrating on the higher modes of vibration, which includes bending mode as well as breathing mode. The developed setup can be modified employing peristaltic pumps which can provide a wide range of pressure pulse variation. These studies are of great importance owing to the superior applications of silicone tube in various fields and especially in the medical field which demands nearly zero percentage malfunction and the flow measurement devices such as Coriolis flow metre which requires very high accuracy.

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