Development of an Experimentation Setup for the Analysis of Flow Induced Vibrations in Flexible Tubes Conveying Fluid

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Abstract

Flexible tubes are used to transfer a wide range of fluids including gaseous fluids and liquids and hence find numerous applications in the industrial field, medical field, etc. Polyurethane (PU) tubes are one among the most widely used flexible tubes owing to their superior qualities and long life. Fluids conveyed through these tubes may not be always in steady condition, rather there are conditions of velocity or pressure varying flow. They can induce severe disturbances to the flexible tube than that induced during the steady condition. These can be extremely hazardous depending on the field of application. So it is needed to investigate the dynamic behavior of flexible tubes in velocity varying flow. Even though vast studies have been conducted in the steady flow through flexible tubes, more experimental studies are needed to be done concentrating velocity.

This paper attempts to introduce an advanced experimental setup for the study of flow-induced vibrations in flexible tubes. Flow is made velocity varying using a linear actuator coupled plunger rod mechanism which varies the flow from zero to maximum value through the plunger movement and this variation in flow velocity results in pressure pulsations in the fluid. The pressure variation is monitored by a pressure transducer and the dynamic responses of the fluid conveying tubes are acquired by means of a Laser Doppler Vibrometer. The experiments are found to be highly useful in the investigation of the dynamic behavior of the flexible tube under pulsatile flow and flow-induced vibration.

Keywords— Flexible tube, Polyurethane, Flow-induced vibration, Velocity, Pressure

Notations

Length of tube, m	= L
Interior Perimeter of tube, m	= S
Inside area of tube, m^2	= A
Linear density of pipe, kg/m	= m
Flexural Rigidity, $Mpa.m^4$	= EI
Coefficient of viscoelastic damping in the pipe, MPa	= E^*
Coefficient of viscous damping, Ns/m	= c
Pressure, Pa	= P
Poison ratio,	= υ
Linear density of fluid, kg/m	= M
Axial fluid flow rate, m/s	= U
Longitudinal tension in tube, N	= T
Transverse shear force, N	= q
Bending Moment, kg.m	= M_b

I. INTRODUCTION

The dynamics of pipe conveying fluid has always been one of the concentrated areas of attention as it shows interesting as well as occasionally nonlinear behavior. Fluid-structure interaction resulting from the transfer of energy from and to the fluid can cause vibrations which can be severe in nature. These vibrations are sometimes hazardous and risky. So it is necessary to study the fluid-structure interaction and flow-induced vibration for practical engineering problems. Internal fluid flow is an important aspect to study the flow-induced instabilities and the dynamic characteristics of fluid conveying pipes. The analysis of natural frequencies of pipe conveying fluid helps to identify the safe operating frequencies of pipes and to design its supports. If the natural frequency of pipe matches with the frequency of structure or other attachment, resonance may occur and it can affect the pipe stability. They can result in leakage and failures.

Many devices which incorporate flexible fluid conveying tubes are now designed for engineering applications, hydraulic machinery application, utilization in hospital, etc. Polyurethane combines the best properties of both plastic and rubber. It offers tear resistance, high tensile and low compression set. It offers high elongation values like rubber and abrasion resistance superior to PVC. Polyurethane is naturally flexible and exhibits superior flexural abilities. As it possesses good chemical resistance with excellent weathering characteristics, polyurethane is superior to most other thermoplastics.

As Paidoussis and Li [1] found, experimental studies on the dynamics of fluid conveying flexible tubes are not numerous even though the theoretical, as well as numerical studies, are many. Naguleswaran and Williams [2] investigated the effect of pressurized flow on natural frequency in a clamped-clamped neoprene tube. Jendrzejczyk and Chen [3] conducted similar experiments on polyethylene and acrylic tubes under various support conditions. All these studies were limited to steady flow conditions and the effects of various parameters like pressure, flow velocity, initial stretch, etc on the critical flow velocity and natural frequency.

Unnikrishnan et. al.[4] discussed an experimental method for calculating dynamic characteristics of horizontal pre-stretched PU tube. Factors affecting modal parameter estimation are found out and optimum parameters are suggested. Zhang et al. [5] conducted an experimental study on pulsating and steady fluid flow in an initially stretched rubber tube subjected to external vibration and found out the effect of flow velocity and stretch rate on the damping ratio.

Velocity varying flow through flexible pipes should be investigated in a detailed way as it can cause more flow-induced vibrations compared to steady flow and also the behavior of the tube can't be predicted. Velocity variation can induce pressure changes to the flow and hence it is a potential area to be studied. The present work is dedicated to the development of a new experimental setup for investigating the flow-induced vibrations in flexible tubes conveying fluid.

II. THEORY

A. Dynamics of Pipes conveying steady fluid

The governing equation for fluid conveying vertically placed slender pipe is presented in Paidoussis [7] as follows. The fluid element is shown in Fig. 1 is subjected to:

- Pressure forces acting on fluid element due to the frictional losses.
- Reaction forces of the pipe, pipe shear force q.
- Gravity forces.

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,

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

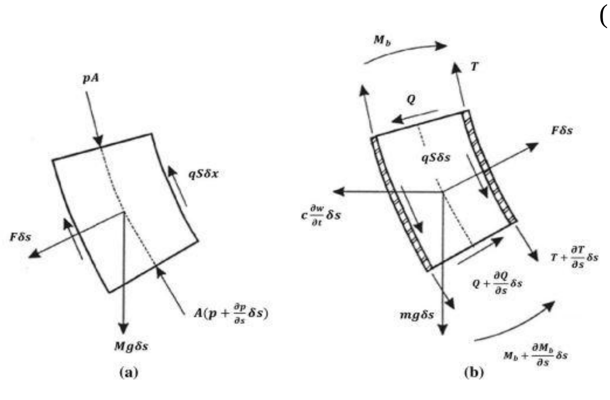

Fig.1 (a) Force balance of a fluid element δs. (b)Force and moment balance of the corresponding element of pipe. [7]

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

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

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

But for velocity varying flow through flexible tubes, internal fluid pressurization is not absent rather it is dominant as the velocity variation causes pressure variation. It is evident from equation (1) that pressurization will cause imbalance to the whole system. Also, the assumption that velocity remains constant is not applicable. So there is a need for experimental study concentrating on the velocity varying flow through flexible tubes.

III. EXPERIMENT ON FLEXIBLE PU TUBE CONVEYING VELOCITY VARYING FLUID

A. Design of Component

A linear actuator – plunger mechanism was devised for the purpose of imparting velocity variation in the fluid flow. In the mechanism, the main components are – A linear solenoid actuator (REMORE 12V solenoid actuator- 25mm displacement), plunger rod and casing. The linear actuator has a stroke length of 20-610mm which can be chosen and a rated maximum load of 7000N. Linear actuator and the plunger rod are mechanically coupled. The plunger rod is placed inside the casing as shown in Fig. 2. In order to prevent fluid leakage, a couple of oil rings are provided at the end of the plunger rod which is coupled with actuator and the plunger is tight fit inside the casing. A spring of low stiffness is placed between other end of plunger rod and casing in order to ensure smooth motion and to prevent metal to metal contact. Spring stiffness is 300N/m and the number of coils is 14.

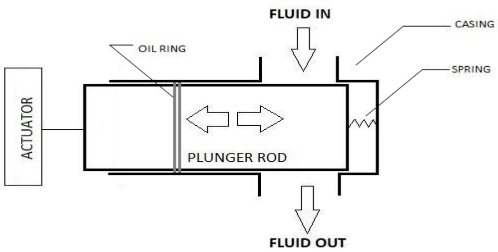

Fig. 2 Schematic diagram of the linear actuator-plunger arrangement

Fig. 3 Fabricated plunger arrangement

The casing has an inlet and outlet opening so that it can be connected to a pipeline. The linear actuator is allowed to move to and fro at high speed and as the plunger rod is mechanically coupled with it, it will also move to and fro. As the movement occurs, it is evident from Fig. 2 that this movement will

ISBN 978-93-89105-41-4

change the flow rate from maximum to zero condition. When the displacement of the actuator is nil, the flow will be maximum and when the actuator displacement is maximum, flow is restricted to a zero condition as the plunger closes the path. This flow rate variation induces a velocity variation and which induces a pressure variation in the fluid flow when continuously operated and thereby desirable flow can be generated. The spring will be compressed at a full displacement of the plunger and it regains the structure as the plunger moves back with actuator. The actuator system can be electronically controlled and so the displacement and speed can be controlled. Velocity can be controlled by controlling the flow rate.

B. Test Facility

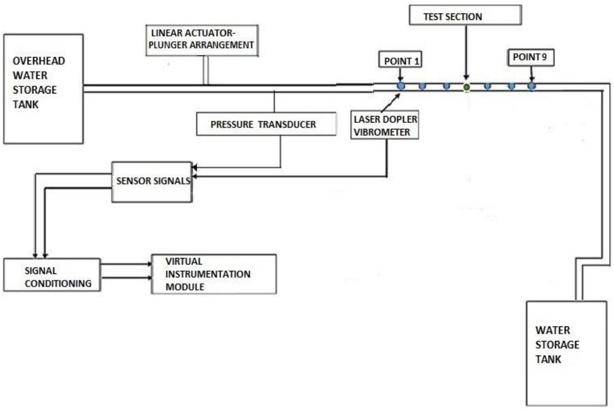

Fig. 4 Layout of the experimental test setup

The test setup consists of a test field, fluid storage tanks, pulsation device, and measurement devices and control devices. A clamped-clamped PU tube placed horizontally is used as a test section. The length of the test section is taken as 36cm and inner and outer diameters are 6mm and 8.5mm respectively. Water is used as test fluid and is filled in the tank and a head of 2m is maintained using a float valve mechanism. A pump is employed to refill the reservoir tank from the collecting tank. Flow is made unsteady using the linear actuator-plunger rod mechanism. It is introduced before the test section. A Pressure transducer [Make: Baumer, Model: ctx 333b220] is introduced in between the pulsation device and the test section to monitor the pressure change which is induced. The dynamic response of the tube can be measured using a Laser Doppler Vibrometer (Model: IVS400, Make: Polytec). Dynamic Signal Analyzers (NI-USB 4431, NI CDAQ 9278 and 9205) are used for the measurement and analysis of acquired signals.

C. Experimental Method

The flexible PU tube was kept horizontal by applying a pre-stretch of 5% of its initial length. Initial pre-stretch was given so as to reduce the sagging of the flexible pipe when fluid is transferred through it. Boundary conditions are made sure by clamping both ends of the test section. The test section consists of 8 equal divisions with fixed points numbered as 1, and 9 as endpoints. For the reflection of the laser beam, reflective tapes are cut accordingly and pasted to the 7 intermediate points of the test section. Laser Doppler Vibrometer is used to analyze the dynamic response from these 7 points.

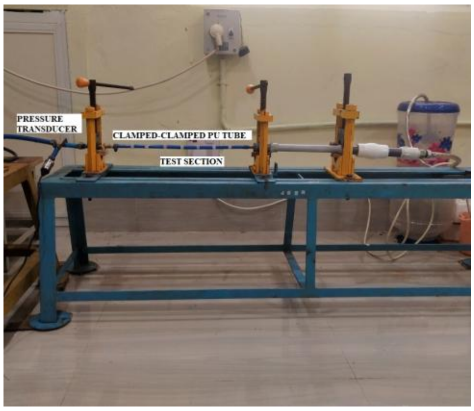

Fig. 5 Test section

The constant head is maintained by means of 2 interconnected above head water tanks and the float valves maintain constant water level inside the storage tank. Fluid coming from the tank is made unsteady by the actuator-plunger rod arrangement and then fed to the test section. The Dynamic Signal Analyzers processes the signals received from the pressure transducer and the Laser Doppler Vibrometer. The post-processing of signals received is done using ME'scope VES analysis software and LABVIEW Signal Express2011 software.

Table 1: Optimum Parameters for data acquisition

Time	
Number of samples	8192
Time resolution (sec)	0.0008
Frequency	
Number of samples	4096
Frequency resolution (Hz)	0.153
No of averages	5
Window type	Hanning

The optimum parameters for data acquisition were adopted from Unnikrishnan et.al. [4]

IV. RESULTS AND DISCUSSION

A PU tube of 36cm length is used to investigate the dynamic characteristics when the tube is subjected to velocity varying flow. The velocity varies from zero to maximum similar to the flow condition resembling a rectified AC signal as shown in Fig.6. When the flow is restricted to no flow condition, the inertia of liquid in the test section will create a negative pressure region and hence the pressure variation will be from a negative pressure region to the maximum pressure region. This forms a pressure pulse and flow tends to pulsatile flow.

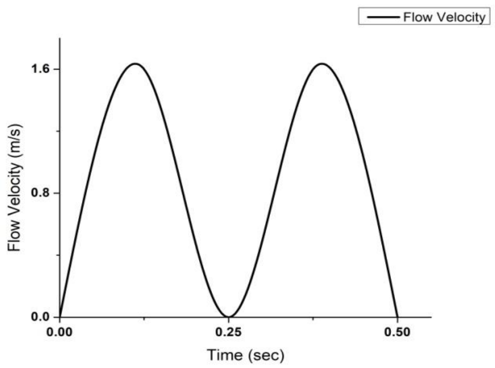

Fig. 6 Flow velocity vs time graph

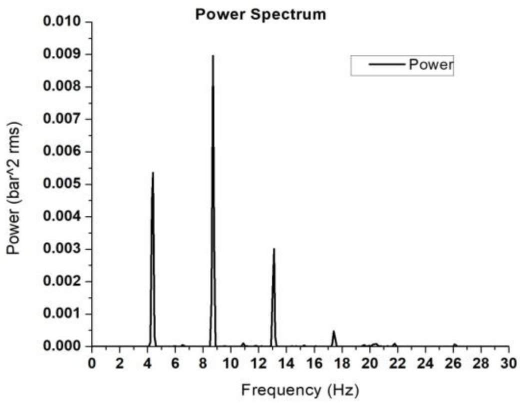

Fig. 7 Power Spectrum obtained from the pressure transducer

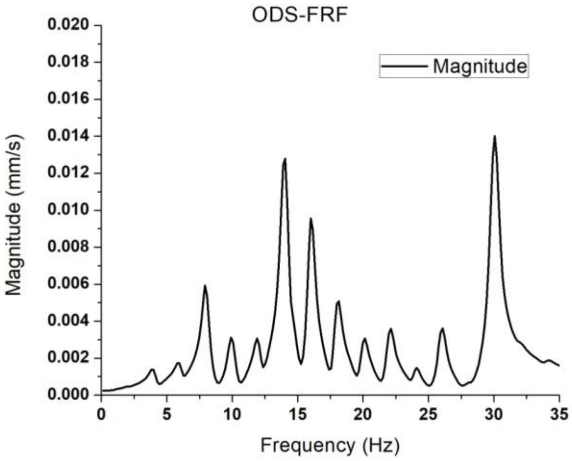

Fig. 8 ODS-FRF obtained from Laser Doppler Vibrometer

Fig. 7 and Fig. 8 represent the power spectrum of pressure pulse obtained from the pressure transducer and Operating Deflection Shape - Frequency Response Function (ODS-FRF) which shows the dynamic characteristics of the flexible tube respectively. The power spectrum represents the frequency of pressure pulse induced in the system. The dynamic response shows the combined effects of pulsation, fluid-structure interaction and flow-induced vibration

As Svete et al [6] explained the interaction of pulsating fluid and tube will result in additional vibrations. The frequencies of these vibrations will be f_1, nf_p, $nf_p + f_1$ and $nf_p - f_1$ where f_1 is the first fundamental frequency, f_p is the pulse frequency and n=1,2,3…

Pulse frequency is obtained from the power spectrum as 4.2Hz. It is evident that there will be vibrations in frequencies ranging from 4.2Hz onwards as shown and these vibrations are the combined effect of pulsation and tube properties. So this setup can be employed to study the dynamic characteristics of flow through the flexible tube with flow-induced vibration.

V. CONCLUSION

This paper brings forward an advanced experimental setup for the study of flow-induced vibrations in flexible tubes conveying fluids. Flow-induced vibration comes in to picture when the steady flow condition is not applicable. Velocity varied flow and pulsed flows are similar conditions where the steady nature of the fluid is not applicable. Hereby means of an indigenously developed plunger-actuator mechanism, the flow velocity could be varied by regulating the fluid flow, thereby resulting in pulsatile flow. The pulse generated can be monitored through pressure transducers and digital signal analyzers. This pressure pulse gives rise to flow-induced vibrations which can be analyzed by means of laser scanning technology and digital signal analyzers. Tests were conducted using the experimental setup and results are obtained. The result reveals the solemnity of the need for further studies related to this area. The setup can be used for the analysis of flow-induced vibrations in flexible tubes conveying fluid.

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