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Development of (Aluminium) U Tube Type Vibration Based Electromechanical Mass Flow Sensor

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Abstract: The Vibration based mass flow sensors offers unprecedented accuracy, robustness and reliability in measuring materials flow in wide range of applications like process industries over more than 20 years. This measures mass flow directly and is not affected by other factors as compared to conventional volume flow measurement techniques such as the density or viscosity of the fluid, or the profile or Reynolds number of the flow. It is a nonintrusive type of sensor, has no moving parts thus reducing maintenance problems. Despite the successful industrial utilization, the performance of such type of sensors is still not fully understood. Therefore, the primary objective of present work is aimed to develop and calibration of the mass flow sensor prototype. This prototype is designed on Pro Engineer Wildfire modeling software and later developed on the basis of theory of vibrating beams, fluid structure interaction and Coriolis technology in the laboratory. This prototype is calibrated successfully for water giving linear relationship between phase shift and mass flow rate as per the classical relationship found in the published literature for various sensor locations as well as drive frequencies. *Copyright © 2010 IFSA.*

Keywords: Mass flow rate, Aluminium vibrating tube, Coriolis force, Laser sensors.

1. Introduction

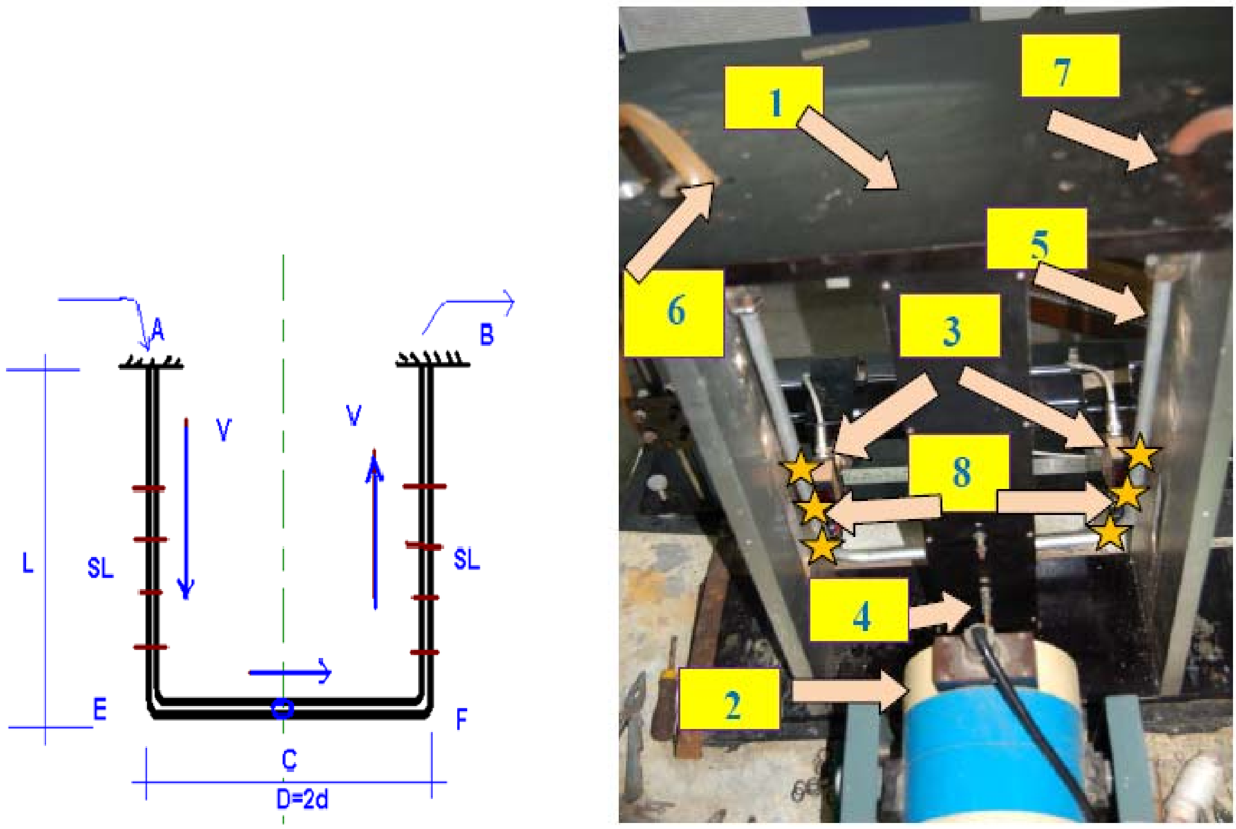
The accurate and quick measurement of mass flow rates of fluids is considered an “enabling technology” in various process industries. Flow sensors based on the Coriolis effect offer the most direct sensing of the mass flow rate, and for this reason do not need complicated translation or linearization tables to compensate for other physical parameters (e.g. density, state, temperature, heat capacity, viscosity, etc.) of the medium that they measure. This also makes Electromechanical mass flow sensors [EMMFS] versatile – the same instrument can, without the need for factory calibration, measure diverse fluid media – liquids as well as gases. Additionally, EMMFS have a quick response, and can principally afford an all-metal-no-sliding-parts fluid interface. Various researchers have been carried out experimental as well as theoretical research on the dynamics of vibrating tube Coriolis mass flow sensors since the 1950s. The major thrust of those studies were to investigate the effects of the fluid velocity, pressure, density, tube geometries and boundary conditions on the natural frequency and the stability of the pipe systems [1-3]. In order to study the measuring and other effects of Coriolis flow sensors, several models, both analytical and numerical were employed/ developed, for the description of the fluid–structure interaction phenomena in the measuring tube. The dynamics of the tube was mostly described by beam models (Euler and Timoshenko models) and the fluid flow in the measuring tube was modelled as a one-dimensional flow [4-9]. A method of modelling the Coriolis mass flowmeter using theory of vibrating beams can be seen in [5]. It is assumed that the tube is made of straight and circular lengths joined together. The use of finite element (FE) models to predict the performance of Coriolis mass flowmeters has become established practice [7-9]. A more comprehensive fully coupled model (with three-dimensional fluid flow) of a Coriolis flow sensor, capable of capturing the actual measuring effects is reported in [8].

A linear variation of time lag with the flow velocity for Coriolis flowmeter having stainless steel U tube with working fluids as kerosene and water has been observed [5]. The Ti-based glassy alloy sensor tube exhibits excellent measurement sensitivity as compared to the conventional flowmeter manufactured using stainless steel (SUS316) tube which reveled the possibility of using others materials having good properties compared to conventional tube materials like aluminium, copper, titanium etc [10]. The experimental studies reported in [11] also gave the same direction of possibility of using other materials but their study was limited to horizontal orientation only. Thus there is a need to develop Coriolis mass flow sensors using others materials like copper, aluminium etc.

The author in his previous study [12] developed the experimental setup and evaluated the performance of vibration based copper U tube Coriolis mass flow sensor. Now the author would like to extend his previous study by using vibrating tube of aluminium tube material with the primary objective to develop and calibration of the U tube aluminium type mass flow sensor prototype by verification of linear relation between time lag and mass flow rate. This involves the development of experimental set up integrated with virtual instrumentation and installed upon a specially designed and constructed foundation using Passive Shock & Vibration Isolation technique [13]. Aluminium has been selected as a tube material because it offers some unique advantages like it is corrosion resistant, has good surface finishing properties compared to conventional used materials. Being more ductile it lends itself to easy fabricability into 'U' shaped tubes. The present study has been carried out with water as a fluid because it generates maximum Coriolis Effect at lower flow rates [1].

2. Working Principle

A Coriolis mass flowmeter measures mass flow directly, using the Coriolis principle, which is based on the conservation of angular momentum, as it applies to the Coriolis acceleration of a given fluid. In principle, as shown in Fig. 1 a Coriolis mass flowmeter consists of a tube with a fixed inlet and outlet, which is vibrated about the axis, formed by the inlet and outlet ends. The tube used in this study is aluminium U shaped, and is vibrated using an electrodynamics vibration shaker attached at point C as shown in figure. Proximity sensors are mounted as indicated in figure and is labelled as SL on two limbs of tube to measure velocity signals from the vibrating tube. This means that liquid flow is measured by transferring vibrational energy from the meter tubing to the flowing liquid and back to the meter. To appreciate this principle, imagine a vibrating tube as shown in Fig. 1.



A - Inlet flow
B - Outlet flow
SL - Sensor Location
C - Exciter position

1 - Test bench
2 - Vibration driver
3 - Laser sensors
4 - Vibration driver rod
5 - U tube
6 - Inlet pipe
7 - Outlet pipe
8 - Sensor locations

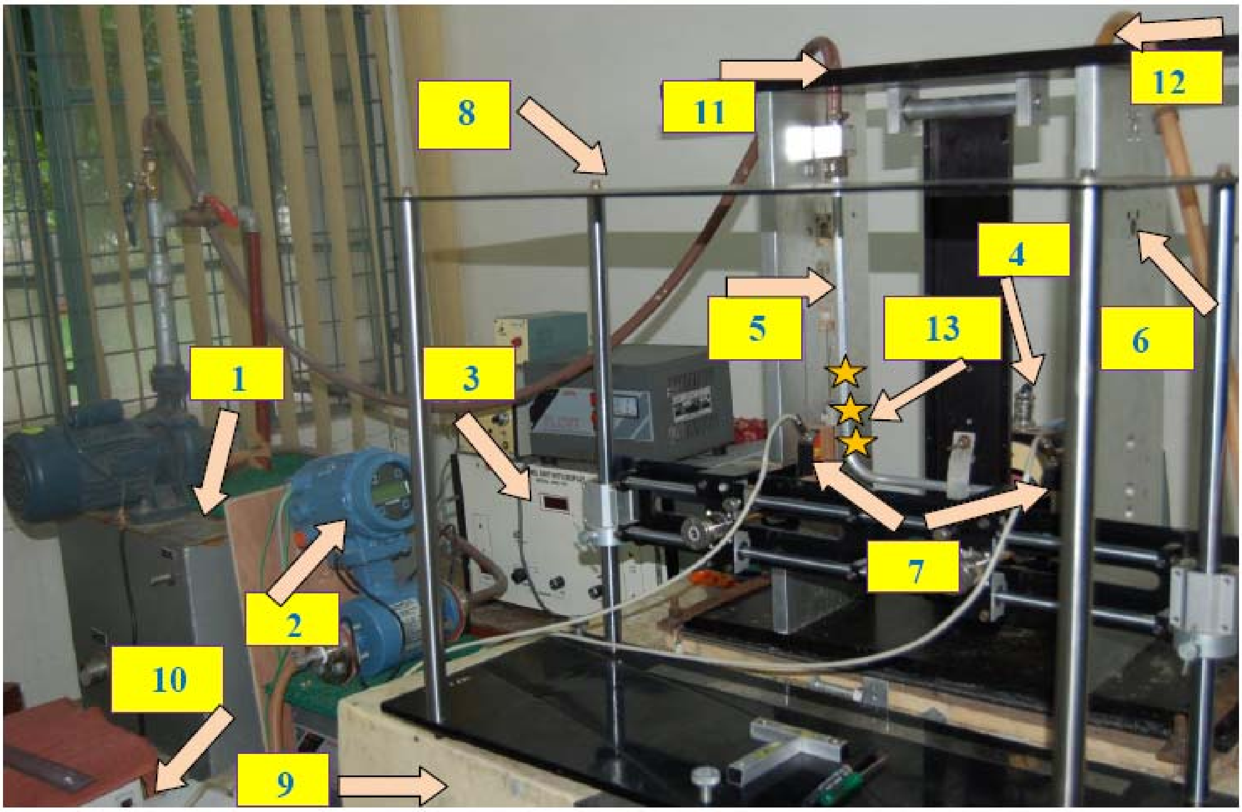
Fig. 1. Oscillating tube conveying fluid along with actual photographic view.

If no liquid is flowing, the excitation in the middle of the tube will cause both arms to vibrate in phase. Mass flowing into the tube starts to receive vibrational energy from the tube walls as it enters the first bend. In this process, the tube loses the same amount of energy. The result is that the phase of the vibrational cycle lags at sensor location of one limbs, the reverse will happen at the location of another limbs. The liquid is vibrating as it enters the bend, but transfers this energy to the pipe. The result is that the mass flow advances the vibrational phase at the sensor location of another limb. When combined, these two changes in vibrational phase produce a twisting of the flow tube. The amplitude of this twist is directly proportional to the mass flow rate and is nearly independent of the temperature, density, or viscosity of the liquid involved.

3. Experimentation

The Experimental set up used in the present study has been designed on Pro Engineer Wildfire modeling software and later manufactured at the Instrumentation laboratory of Mechanical and Industrial Engineering Department, IIT, Roorkee. The block diagram of the experimental setup has been shown in Fig. 2, which consists of the several functional elements such as: Hydraulic bench for providing regulated water supply to the flowmeter. Test bench for supporting the tubes of the Coriolis mass flow sensor. Excitation system for providing mechanical excitation to the Coriolis mass flowsensor, consists of an Electrodynamics shaker, control unit, accelerometer and vibration sensor.

Virtual instrumentation comprising of non-contact inductive proximity sensors, and a signal conditioning unit as shown in Fig. 2.



Various design components are as follows:

1 - Hydraulic bench	5 - U tube	9 - Foundation	13 - Sensor locations
2 - Electromagnetic flowmeter	6 - Test Bench	10 - Data Acquisition box	
3 - Vibration Control unit	7 - Laser sensors	11 - Inlet pipe	
4 - Vibration driver	8 - Sensor holding stand	12 - Outlet pipe	

Fig. 2. The photographic view of the experimental setup.

3.1. Experimentation Scheme

The design parameters varied in this study are flow range between 0 to 0.3 kg/sec, the details of these have been shown in Table 1 as below. Inductive proximity sensors have been used for motion sensing as these are sensitive to metal objects, they are helpful in eliminating any unwanted noise generated from the surroundings and inherently resistant to dust, humidity and oil in industrial environment. The vibration shaker used in the present study which provides the desired excitation to the Coriolis Mass Flow Sensor. This is having amplitude of 5 mm peak to peak and an excitation frequency in the range of 1 Hz to 1 kHz. In order to make a contact a mild steel rod of 5 mm diameter is used as a stinger to transfer the motion to the knife edge support. As the exciter uses a lot of power and generates a lot amount of vibrations, a strong isolated base was provided so as to damp the vibration and thus avoid movement of exciter or transfer of stray vibrations to the sensor stand or the testing bench [1, 2, 13]. The present work utilizes the concept of Virtual instrumentation platform to perform the fast data analysis. Data acquisition and its processing can be conveniently implemented on a digital platform. For ease of coding, a PC platform is chosen as the processing hardware. For acquiring the signal from the sensors to the PC, NI DAQ card (USB-6211) is used. It consists of two 32 bit counters operating at

80 MHz. It also consists of a 16 bit A/D converter operating at 250 kS/s which continuously samples the signal. A visual programming language (LabView) is used for processing the data in real time.

Table 1. Input Parameters.

Tube shape	U type
Tube material	Aluminium (E =70 GPa, k = 0.3)
Tube dimensions	Do=12.7 mm ; Di=10.9 mm
Height of vertical arm of tube	L = 40 cm
Distance between two arms	D = 40 cm
Sensor Location range	SL = 6 to 12 cm
Drive Frequency range	DF = 32.7 to 34.7 Hz
Mass flowrate range kg/s	0.1 to 0.3
Fluid	Water

3.2. Experimental Procedure

The details of the experimental procedure used to conduct the present study have been described in Fig. 3 as shown below. The hydraulic unit for providing regulated water supply to the mass flow sensor. The hydraulic unit derives its power from the constant voltage transformer (CVT) to maintain constant flow rate. The U-tube is made to vibrate using an electronic shaker. An accelerometer is attached to the shaker which measures the velocity, amplitude and acceleration of the vibration induced by the electronic shaker. The accelerometer gives the feedback to the vibration meter which is observed for maintaining the constant amplitude.

A pair of proximity sensors has been placed on the mechanical positioning attachment facing the two limbs of the U-tube. The output terminals of the sensors have been connected to the input of the NI-DAQ through a signal conditioner. NI-DAQ has inbuilt counters which operates at 80 MHz. These counters measure the frequency and the edge separation between the two incoming waves. The edge separation between the rising edges of the two waves is the time lag (Δt) required for calculating the mass flow rate. The processing of the signals, calculation of the mass flow rate and displaying of the results is processed in LabView. The LabView takes the parameters of the U-tube and other settings as inputs from the user and calculates the mass flow rate which is displayed on the screen. Accuracy and repeatability for each experiment was achieved with the same input conditions until stabilized output was achieved.

4. Results and Discussion

The primary objective in the present study is to verify the linear relation for Phase shift and mass flow rate therefore experimentation was carried out for the set of input design parameters as mention in Table 1. All these results have been explained in details in the following paragraphs through Figs. 4 to 7. The Fig. 4 depicts the variation of experimental phase shift Vs mass flow rate at various drive frequencies from 32.7 to 34.7 Hz for sensor location 6 cm. It may be noticed that there exists an accurate linear relation between phase shift and mass flow rate for drive frequency 33.7 Hz compare to two other closer frequency with maximum phase shift.

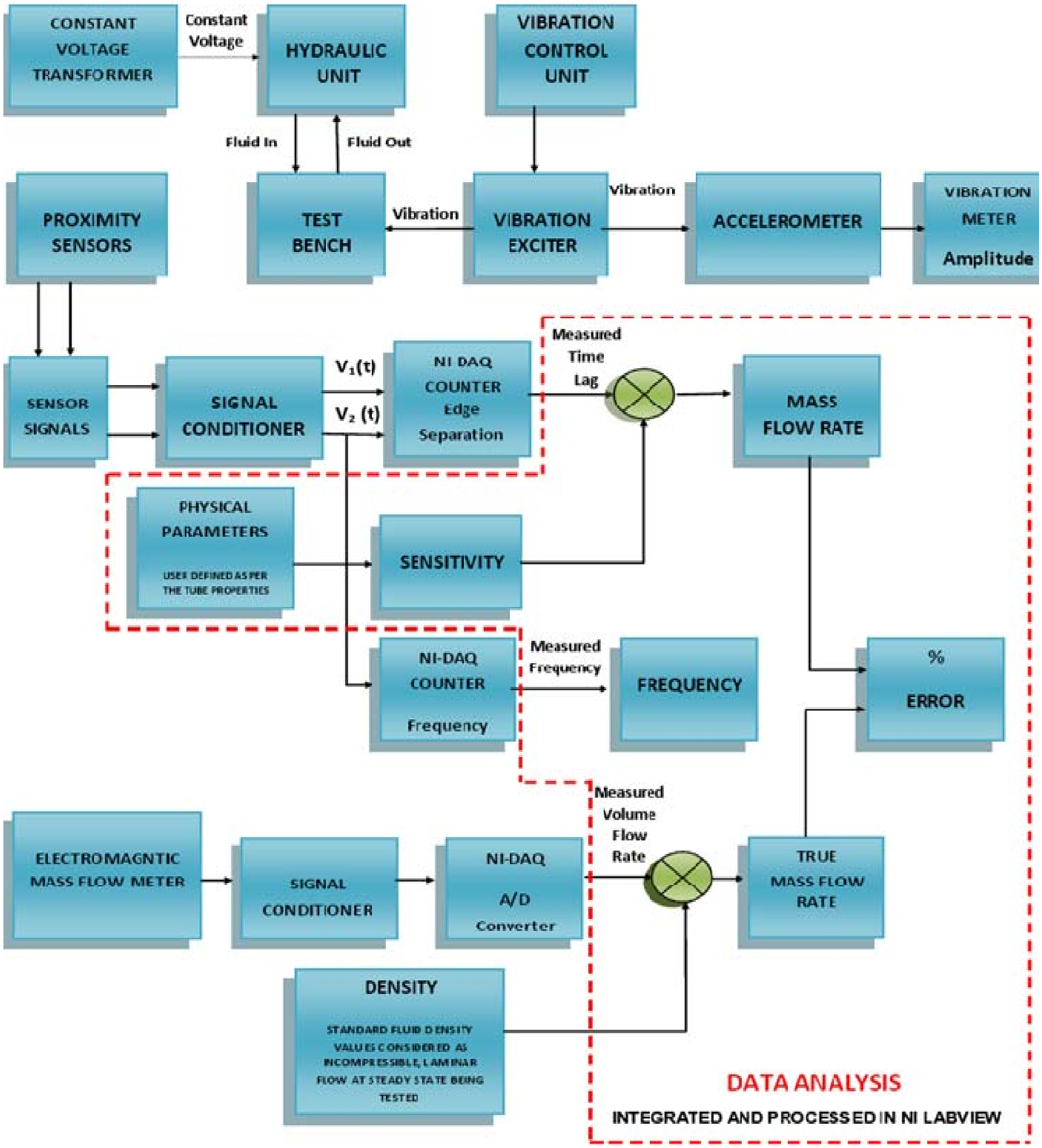


Fig. 3. Flow diagram describing experimental procedure.

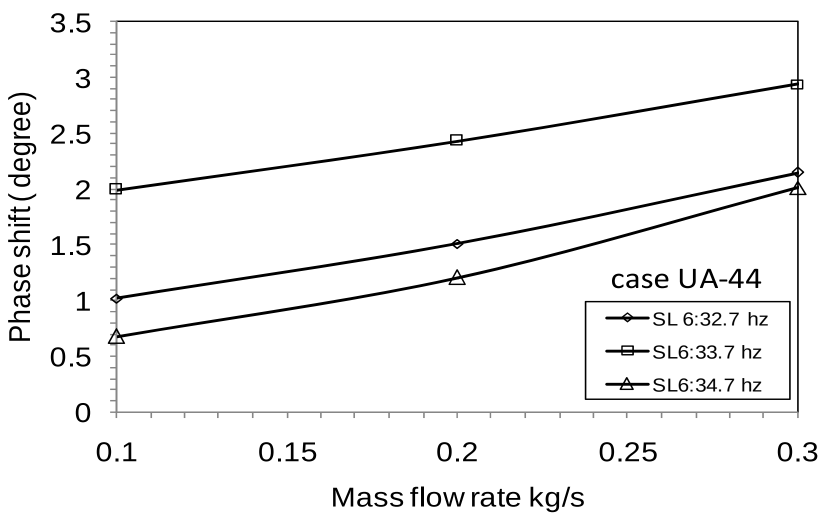


Fig. 4. Phase shift verses mass flow rate for SL 6 cm at various drive frequencies.

The Fig. 5 explained the variation of experimental phase shift Vs mass flow rate at various drive frequencies from 32.7 to 34.7 Hz for sensor location 9 cm. It may be noticed that there exists linear relation between phase shift and mass flow rate for drive frequency 32.7 Hz compare to two other frequency.

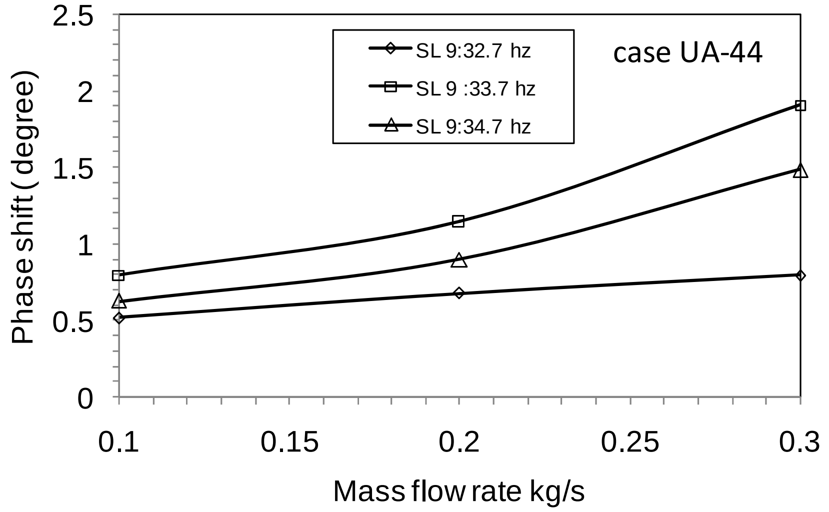


Fig. 5. Phase shift verses mass flow rate for SL 9 cm at various drive frequencies.

The Fig. 6 showed the variation of experimental phase shift Vs mass flow rate at various drive frequencies from 32.7 to 34.7 Hz for sensor location 12 cm. It may be noticed that there exists linear relation between phase shift and mass flow rate for all drive frequencies however maximum phase shift is observed for 33.7 Hz.

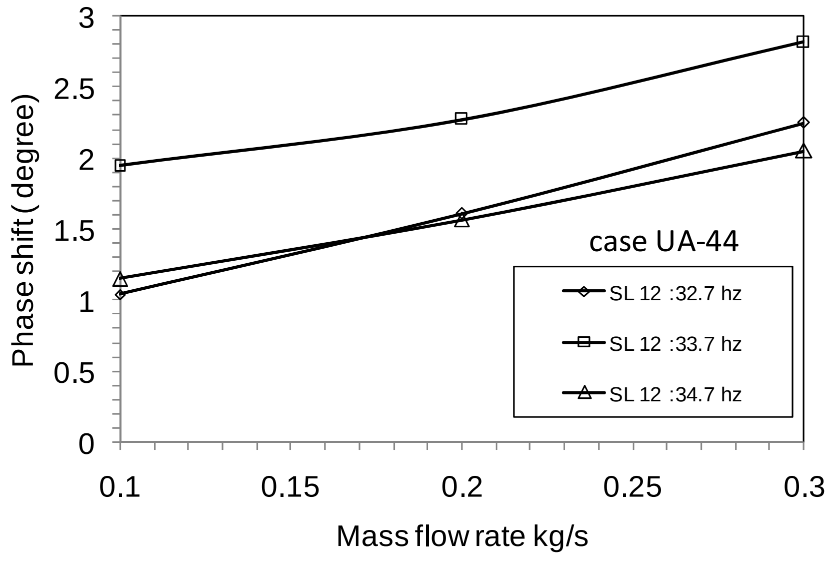


Fig. 6. Phase shift verses mass flow rate for SL 12 cm at various drive frequencies.

Thus from the above discussions and Fig. 7 it may be observed that linearity is exits between phase shift and mass flow rate which is consistent with the results of earlier reported literature [5 and 11]. The more linearity as well as phase shift may be observed as shown in Fig. 7 for 33.7 Hz drive frequency at 6 cm from the bottom of the tube in vertical direction compare to other drive frequencies and sensor locations. From Fig. 7 it may also observed that less linearity exists for frequencies less or more value of natural frequency in present case 32.7 and 34.7 Hz at different sensor locations giving lesser phase shift compare to fundamental natural frequency suggesting that there is a need for proper selection of these parameters for accurate mass flow sensing.

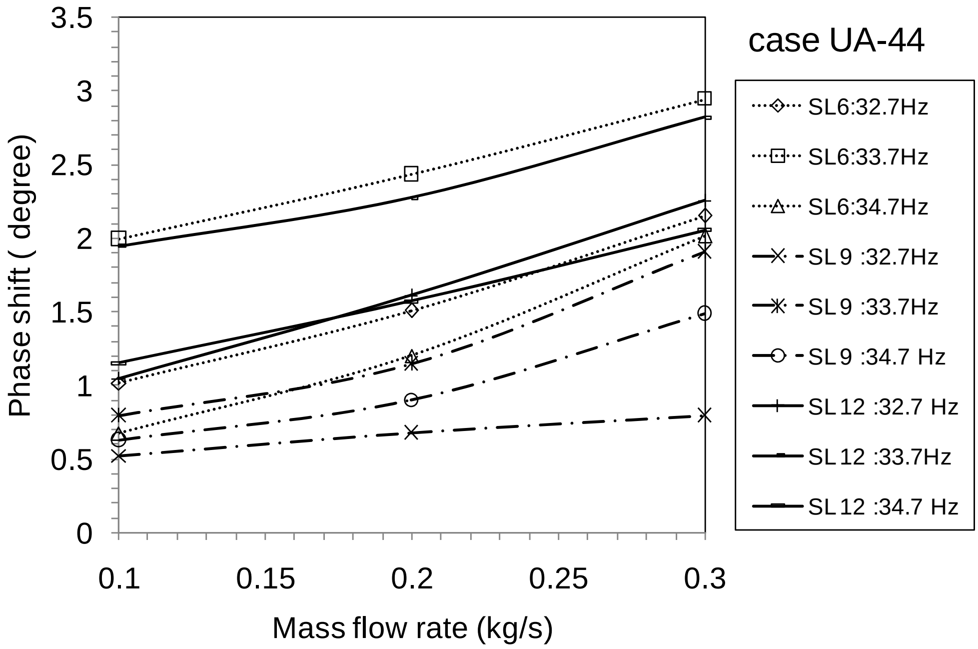


Fig. 7. Phase shift verses mass flow rate at various drive frequencies for all SL.

5. Conclusions

The experimental set up is designed on Pro Engineer Wildfire modeling software and later developed on the basis of theory of vibrating beams, fluid structure interaction and Coriolis technology in the laboratory integrated with virtual instrumentation. Further using the Passive Shock & Vibration Isolation technique the setup installed upon a specially designed and constructed foundation. The calibration of the U tube aluminium type mass flow sensor prototype by verification of linear relation between phase shift and mass flow rate is carried out for fluid as a water as per the classical relationship found in the published literature for various sensor locations and drive frequencies.

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Guide for Contributors

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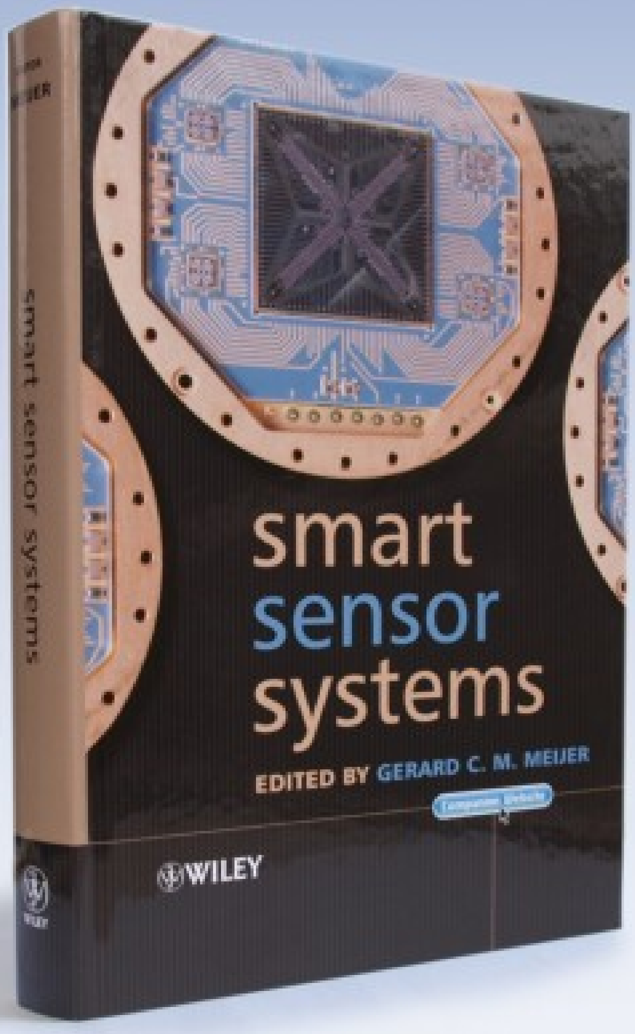
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