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Research Article

Liquid Density Measurement using Tuning Fork

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Abstract

A low cost sensor equipped with a tuning fork is proposed, to provide liquid density measurement with a portable method. The sensor is based on the resonance theory and has precise accuracy for the application. The device is composed of sensor, driving electronics and a computer unit for density calculation. The tuning fork vibrates at its natural frequency in the air, when immersed in the liquid the fork frequency is damped due to the added mass of the fork. This damped frequency is evaluated and calibrated to show the density of the liquid under consideration.

Keywords: *Tuning fork; portable method; precise accuracy; natural frequency; damped frequency; density.*

1. Introduction

Density is measured in terms of mass per unit volume but in some applications it is expressed in terms of dimensionless quantity, specific gravity or relative density.

$$\rho = \frac{m}{v} \qquad (1)$$

Where m is mass and v is volume and ρ is density in kg/ m^3. Density is one of the most important physical properties of liquid which is used to understand the other chemical and physical properties like thermal coefficient of expansion (Lagourette.B. Boned.C, Saint-Guirons.H, Xans.P, *et al*, 1992)

The tuning fork is used because it is not affected by external sources of vibration and only depends upon the properties of the material, added mass due to liquid, temperature and pressure.

This paper proposes a low cost design to provide the direct density value at the petrol stations or gas stations.

The sensor is composed of sensing unit and a density calculation unit. The liquid density is directly sensed by the resonant tuning fork. The pickup element sends the measurement information to the Microcontroller for processing. After calculation it gives the density value.

Initially this method was developed for monitoring the retrieval operations from the radioactive waste storage tank at Hanford site in eastern Washington State (USA) which was installed on line and can be used in other applications (Greenwood, M.S. Lail, J.C., *et al*, 1998; Greenwood, M.S, Skorpik, J.R, Bamberger, J.A, *et al,* 1998). At present the study on the liquid density measurement all over the world is converged on the ultrasonic principle but these devices managed to achieve accuracy of only 0.1% (Püttmer.A, Hauptmann. P, Henning.B,) which is still less as compared to laboratory measurements which achieves the more accuracy.

The existing devices which are used for measuring density at petrol or gas stations are very high in cost and they are installed online in large tanks. A portable liquid density measurement sensor is proposed, which can be used to measure the density of the liquid from the sample of the petrol. It can measure the density directly with the use of tuning fork. The tuning fork is placed inside the measuring assembly in this proposed approach.

The sensor can be used to provide density at petrol filling stations, for providing the density reference to customers and also in other application for measuring the density of the sample provided. At petrol station there are some customers who want to see the density when they are filling the petrol.

The impact of the structural parameter, temperature and liquid on the natural frequency of the tuning fork are theoretically shown.

This shows the dependence of resonance frequency of the fork on parameters and material used in the fork. A pulsed current power supply is designed for the tuning fork sensor. Sensor output is in the form of pulse frequency modulation (PFM) and is evaluated using a micro-controller. By storing the specific medium properties and mathematical relations in the system the density is calculated.

Temperature compensation for density of liquid and for sensor material is also carried out in development of the project.

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2. Theory Analysis

2.1 Working Principle

The tines of the tuning fork precisely have to vibrate at its natural frequency during the process. The equivalent mass and the stiffness of the sensor material constitute this frequency. To achieve this frequency is very critical part of sensor fabrication. Frequency of tuning fork in air as a medium is its natural or resonance frequency.

The tuning fork is excited by a piezoelectric drive element. When alternating voltage is applied to piezoelectric material it contracts and expands. This alternating voltage is transmitted by actuator to make tuning fork vibrate at its resonance frequency.

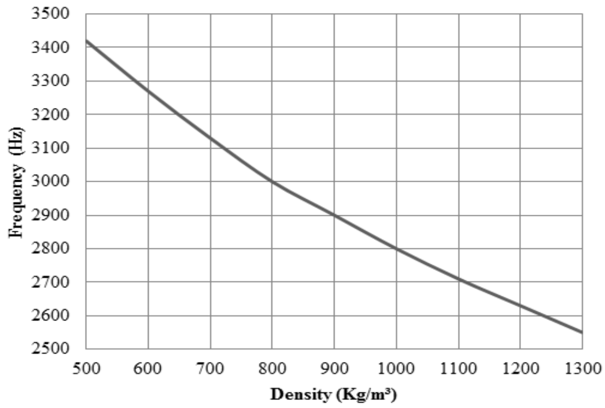

Fig.1 Natural frequency of the tuning fork changes with liquid density

The tuning fork and excitation signal is provided by the driving electronics from the Endress+Hauser, India (Technical Information from Endress+Hauser, India). The tuning fork is excited by piezoelectric method. The vibration of the tuning fork is sensed by a pickup piezoelectric element. It forwards the signal in the form of pulse frequency modulation continuously to computer unit for density calculation.

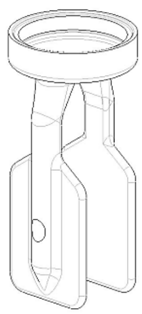

Fig.2 Tuning fork

When the tuning fork is placed in a media for example liquid, the mass of the fork changes due to liquid around it and thus there is a change in the frequency or vibration cycle of the fork.

The pickup piezoelectric element detects this frequency. This change in frequency is the measure of density. The natural frequency of the tuning fork is important to achieve the desired result.

By measuring the changes in the frequency or vibration cycle, the density of the liquid under test can be determined.

2.2 Resonance Frequency of tuning fork

The natural frequency of the tuning fork plays an important role in the sensor performance. This frequency depends upon the dimension and material used in tuning fork. To achieve the desired resonance frequency different fork parameters are considered with a precise accuracy and safety measures.

2.3 Resonant frequency in air

The vibration of the tines of the fork can be considered equivalent to the vibration of cantilever beam. The vibration frequency is obtained by using Euler's equation given as.

$$f_{\mathrm{r}} = \frac{(\beta_r l)^2}{2\pi}\sqrt{\frac{EJ}{\rho A l^4}}, r = 1, 2 \ldots. \quad (2)$$

Equation (2) shows that the vibration frequency of cantilever beam depends upon cross sectional area and length (Wang, B. Analysis and Application of Vibration, *et al*, 1992). Where ρ is the mass per unit volume (density), A is the cross sectional area, l is the length EJ is the bending rigidity of the cross section, and β l can be calculated from the equation

$$\cos\beta l = \frac{-1}{ch\,\beta l} \quad (3)$$

For achieving a natural frequency, length and cross sectional area of the tines of the fork are considered. Thus for a tuning fork this frequency constitutes for frequency in air. The resonance frequency of sensor used in this project is around 300-1500 Hz.

2.3 Resonance frequency in liquids

Similar to the study of free cantilever beams under liquid (Yeh.L. *et al*, 1974) it is assumed that liquid is ideal, incompressible and without spin, and based on the Laplace equation.

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \quad (4)$$

Liquid velocity potential function is ϕ (x, z, t) and changes of vibration frequency of the cantilever beam in liquid, when depth of beam in liquid changes (Dezhi Zheng, Jiying Shi and Shangchun Fan, *et al*, 2012) is given as,

$$f' = \frac{f_{\circ}}{\sqrt{1+0.183\frac{4\rho' h}{\pi\gamma}}} \quad (5)$$

$$\rho' = \frac{(f_o^2 T^2 - 1)\pi\gamma}{0.732h} \quad (6)$$

Equation (5) and (6) shows similar to cantilever beam frequency of the tuning fork changes when the depth in the liquid or density of the liquid changes.

In (5) and (6) f_o is natural frequency of the tuning fork in the air, ρ^' is the liquid density, T is the vibration cycle of the tuning fork, T=1/f. When tuning fork is immersed in a liquid, its vibration frequency decreases as its depth in the liquid increases. If depth is fixed, the decrease in the vibration frequency depends only on the liquid density.

Generally following equation is used to calculate the density.

$$\rho' = m_o + m_1 T + m_2 T^2 \quad (7)$$

Equation (7) shows the relationship between the liquid density ρ' and vibration cycle T of the tuning fork T=1/f ', and m_o, m_1 and m_2 are sensor coefficient determined through calibration experiments from Endress+Hauser.

2.4 Resonant frequency dependence on temperature

Performance of the sensor is affected by temperature. The effect of the temperature on natural frequency of the tuning fork is due to elastic modulus of the material used.

$$E = E_o(1 - \eta T) \quad (8)$$

Equation (8) shows that the elastic modulus of metallic materials decreases linearly with increasing temperature (Dezhi Zheng, Jiying Shi and Shangchun Fan, *et al*, 2012) and depends on the temperature coefficient η of the elastic modulus E.

$$E = E_o(1 - 25\alpha T) \quad (9)$$

Equation (9) is the general form of elastic modulus of metallic material changes with temperature, α is linear expansion coefficient.

For most of the metallic materials value of α change as temperature increases, but for small change it could be considered as constant. Vibration frequency of tuning fork will take the form:

$$f_r = \frac{(\beta_r l)^2}{2\pi} \sqrt{\frac{E_o(1-25\alpha T)J}{\rho A l^4}}, r = 1, 2 \ldots \quad (10)$$

Where α is linear expansion coefficient of the metallic materials, T is kelvin, E_o is elastic modulus at absolute zero, ρ is density of the metallic materials, J is the moment of inertia, A is the cross sectional area, l is the length.

Equation (9) shows that an elastic modulus changes with temperature, (10) gives the effect of temperature on the resonance frequency of tuning fork.

If there are minor changes in temperature then there are uniform changes in the length, to the original length of metal depending on the composition.

Thus a temperature sensor is used in the system to detect the liquid temperature and measured in real-time to compensate for the changes in the elastic modulus of the tuning fork.

2.5 Thermal expansion in solids and liquids

Due to increase in temperature the vibrational amplitude of the atoms in the crystal lattice of the solid also increases. The average spacing between the atoms increases as well as the total volume V (at constant pressure P).

$$\alpha = \frac{1}{V} \cdot \left(\frac{\partial V}{\partial T}\right)_P \quad (11)$$

Equation (11) is called the volume expansion coefficient at constant pressure.

As temperature increases, a greater thermal agitation of the molecules occur in liquids and therefore it causes an increase in its volume (though, water between 0 and 4°C is an exception to this).

The volume specific coefficient of expansion shows the value by which the volume of a medium changes with temperature.

The coefficient of expansion or volume expansion coefficient of olive oil, water, petrol depends on temperature. Measured values at 20°C are shown in table 1.

The coefficient of expansion of steel and aluminum depends on the composition of metal used. The coefficient is calculated for the application range and is applied for this specific range to compensate for the temperature changes.

3. Proposed System for Density Calculation

Density is calculated with a microcontroller by calibrating the frequency of the tuning fork, and compensating for Changes in temperature.

There is no need for compensating changes for the pressure because the proposed system would be working under atmospheric pressure which is constant.

Table 1 Volume Coefficient of Expansion

Material	Volume Coefficient of expansion $\frac{\alpha 1}{10^{-3}K}$ or $\frac{\alpha 1}{10^{-3}°C}$
Aluminium	2.2
Brass	1.8
Copper	1.6
Olive oil	0.7
Glycerol	10.59
Petrol or Gasoline	0.95

The density is calculated first acquiring the value manually and then calibrating it in accordance with the frequency at the sensor output. That frequency is evaluated as the density of the liquid.

Temperature compensation is also achieved both for the liquid and sensor material.

3.1 Current Power Supply for Electronics

The current power supply for the driving electronics (FEL50D) by Endress+Hauser is designed as the part of this project. The power supply requirement for FEL50D driving electronics is:

1. Frequency: 300-1500 Hz
2. Pulse height: 16 mA
3. Signal level: 4 mA
4. Pulse width: 20 µs

The tuning fork vibrates at its natural frequency when pulsed current power supply is given.

When it is immersed in liquid there is a change in the frequency compared to the resonance frequency. The resonance frequency is considered as reference for measuring the density which is nothing but the deviation of frequency.

By using mathematical relations and frequency of the fork after it is immersed in the liquid, the liquid density is determined.

For compensating the temperature changes, a temperature sensor is also used in the system. There is some mathematical calculation is done in system for temperature compensation. And result of actual density is displayed.

Figure (2) shows the block diagram of the proposed hardware.

3.2 Sensor Output

The sensor output is in the form of Pulse Frequency Modulation (PFM). These PFM pulses are in the same form as applied from input current power supply.

The measurement information is contained in the frequency variation at the output of the sensor. Depending upon this change in frequency the density is measured.

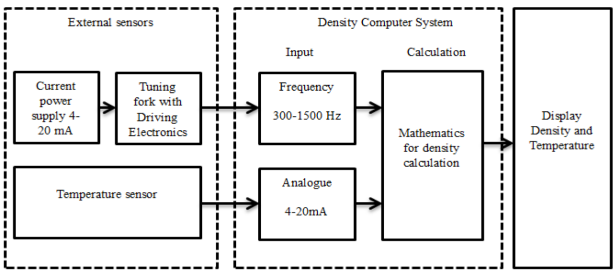

Fig.3 Block Diagram of Proposed system

3.3 Compensation for Temperature Changes

The temperature sensor is used to compensate the changes in elastic modulus of sensor material and the liquid density based on the volume expansion coefficient.

The volume expansion coefficient is calculated for the operating range and is used in compensating the changes for temperature for operating range.

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