Inductive Flow Sensor for Fluid Velocity Measurement in Pipelines

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***Abstract* —This paper proposes an inductive flow sensor that uses the displacement of a paddle-cantilever system caused by fluid pressure for measuring the velocity of the flow of surrounding fluid, using inductance reactance variation due to change in frequency of alternating current powering the inductor. The simulation process is done in the AC/DC module provided along with the COMSOL software package. An inductive coil with a magnetic core and alternating current passing through it is used as the transducer for the flow sensor. Simplicity of simulation, possible zero power consumption design in the future and low cost fabrication combined with insensitivity to variations in fluid stream properties makes this sensor ideal for widespread deployment in most fluid pipelines**

***Index Terms*—Flow sensor, Inductive reactance, Pipeline fluid flow, Flow measurement, Inductor.**

I. INTRODUCTION

Currently, cost plays a major role is the popularity and inhibition of widespread deployment of flow measurement sensors. The capacitive dynamic pressure displacement sensor technique reduces the cost factor using MEMS technology but is a non-linear system as the capacitance varies with change in gap between capacitance plates [1]. Other commonly implemented MEMS flow sensors are usually designed on the basic principles of asymmetric thermal conduction [2, 3, 4, 5]. Asymmetric thermal conduction uses a heated filament to heat the fluid and then measure the heat at various points on the pipeline. The faster the heat is detected at various points in the pipeline the faster the flow of fluid. However, placement of a heated filament in a potentially combustible gas mixture is not possible due to intrinsic safety requirements of natural gas pipelines.

Here a frequency varying inductor coil sensor is designed with a possible MEMS future that allows for low cost fabrication and has linear characteristics. The measured quantity here is the inductive reactance of the system which varies linearly with the varying frequency of the system. The quantity to be found is the flow velocity or flow rate of system.

The complete step by step process of measuring flow rate from the inductive reactance is explained here.

II. DESIGN

The design of the flow sensor system is meant to be simple yet robust when it comes to its performance. The basic block diagram showing various parts of the system is shown in figure 1. A power source powers the inductor coil and frequency varying mechanism. The reference pressure holds the fluid at any pressure as decided by the designer, here vacuum pressure is chosen. The measurement system measures the inductive reactance of the inductor coil whose inductance value remains constant. The frequency varying button changes frequency of the alternating current supplied to the inductor coil according to the position it is in with respect to its rest position. The frequency varies and hence the reactance varies. The frequency varying push button is implemented using variable frequency drives (VFD) of appropriate MHz range, easily available in the market. VFD takes the incoming alternating current rectify it into direct current and then invert it back into alternating current while changing the frequency of the current as desired. This VFD is fit with a spring button mechanism to transfer the pressure on the button into frequency. The fluid flow pressure causes the frequency varying spring loaded push button to be at a certain position for a certain pressure. Thus when pressure changes; it changes the position of the frequency varying button and hence the frequency varies.

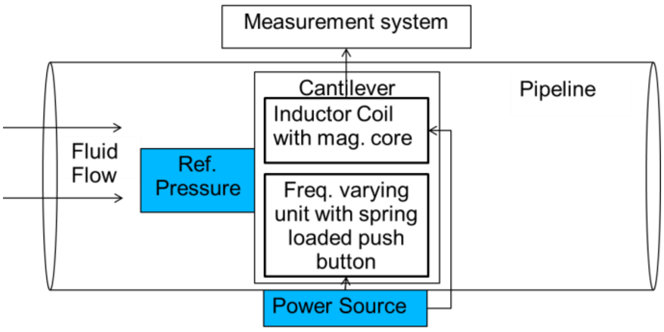

Fig. 1. Block Diagram of proposed scheme showing all required blocks.

When fluid flow velocity varies causing a change in pressure, the new pressure proportionally pushes or releases the spring loaded frequency varying button. Therefore there is a linear relation between pressure and the position of the button as shown below.

$$F = kx \qquad (1)$$

$$P = \frac{F}{A} \qquad (2)$$

$$P = \frac{kx}{A} \qquad (3)$$

Where *F* is the force experienced by the surface area *A* of the frequency push button due to the pressure *P* of the fluid and *x* is the distance the spring in the spring loaded button with spring constant k is moved from its equilibrium position. The change in frequency caused by the pressure causes the inductive reactance to change according to the following formula.

$$X_L = 2\pi f L \qquad (4)$$

Where X_L is the inductive reactance of the inductor coil, *f* the frequency of the alternating current passed through the coil and *L* the inductance of the coil which remains constant throughout the entirety of the flow sensors lifetime.

The inductive reactance of the inductor coil is measured by any of the modern day methods of measurement, a multimeter or digital software designed especially for the sensor along with wireless technology to transfer the data acquired by the sensor to anywhere it is needed. Once the inductive reactance is known, equation 4 is used to find the frequency of the alternating current. Equation 4 shows the linearity of the system being designed that is the inductive reactance varies linearly to the frequency of the alternating current and so at no point in the measurement will either inductive reactance or frequency stop varying with respect to the other.

Now that the frequency corresponding to a particular inductive reactance is known, the pressure corresponding to this frequency is to be found. The frequency varying push button is designed in such a way that every unit change in position of button causes a linearly proportional unit change in frequency. Since the corresponding values of frequency and position are known via experimentation with the designers choice of frequency varying mechanism, the position corresponding to a particular frequency can be found using equation of a line.

$$\frac{(x - x1)}{(x2 - x1)} = \frac{(f - f1)}{(f2 - f1)} \qquad (5)$$

Where *x1, x2, f1, f2* are known values of position and frequency respectively. These could be taken as the start and final values of frequency and position, but it is up to the designer on how to select these values.

From equation 5 a position *x* is found corresponding to the frequency *f* found using equation 4. Now that the position *x* is known, use equation 3 to find the pressure of the fluid at the surface of the push button. Using Bernoulli's equation given below the velocity of the fluid corresponding to the pressure seen at the frequency varying button is found out.

$$V = \sqrt{2P/\delta} \qquad (6)$$

Where *V* is velocity of the fluid, *P* the pressure difference between fluid pressure at button and pressure of fluid in vacuum and δ is the density of the fluid. From the velocity calculated the volumetric flow rate is calculated as given.

$$Q = AV \qquad (7)$$

Where *Q* is the volumetric flow rate, *A* is the cross-section area of the pipe and *V* the velocity.

The basic design principle discussed in this section is incomplete without the simulation of the inductor coil and the graphical representation of the simulation result showing the linearity allowed by this method of fluid flow sensor implementation.

III. SIMULATION OF INDUCTOR COIL

Simulation of the inductor coil characteristics is done on the AC/DC module of COMSOL multiphysics software. Firstly the 3D structural model is designed. The 3D model is designed such that it complements and develops on how flow sensors are generally built (small in size, non-polluting and easy to pack is tight spaces). Shown in figure 2 is the 3D model of the inductor block created in COMSOL. The black and white terminals are the input terminals of the alternating current whose frequency will be changed before applying it to the inductor by the VFD. The orange/yellow semi circles are part of the inductor winding which is shown more clearly in figure 3. The blue part seen around and within the winding is the magnetic core. The spherical lines around the core show the magnetic field extremities.

Once the model was designed, the material of each part needs to be specified. Select copper as the material for the inductor winding. The material of the area around the core is selected as air (or the fluid the sensor is being designed for). For the core a new material is created within COMSOL named core with designer specified parameters. The parameters depend on what material is being used as the magnetic core. If the material being used isn't already available by default in COMSOL, create it and provide the required parameters that would be needed to solve any studies performed later on the 3D model. For simplicity purposes current simulation was done using an imaginary material.

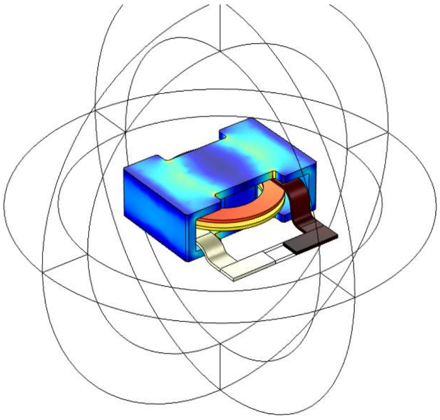

Fig. 2. 3D model of inductor model showing magnetic field, magnetic core, inductor winding and input terminals of alternating current.

The parameters were defined as follows. The electrical conductivity of this material was taken as 0, relative permittivity as 1 and relative permeability as 1000.

As explained earlier figure 3 shows a clearer more precise model depiction of the inductor winding. The winding has 3 turns and 2 terminals for the alternating current inputs. The designer can choose the material of the winding as required, but in most cases copper winding tends to be in use and hence copper was used in this study of the inductor sensor system.

After the materials are defined a study is done on the 3D model by varying frequency of the alternating current and noting the corresponding inductive reactance. This is then plotted graphically as shown in figure 4. The linearity of this sensor is clearly shown in this graph. This linearity couldn't be achieved by the capacitive method of sensing [1] due to the fact that the sensor used the pressure of the fluid to change the gap between capacitance plates and then measure the capacitance. The inversely proportional non-linear relation between the capacitance and gap is removed in the frequency varying inductor coil system.

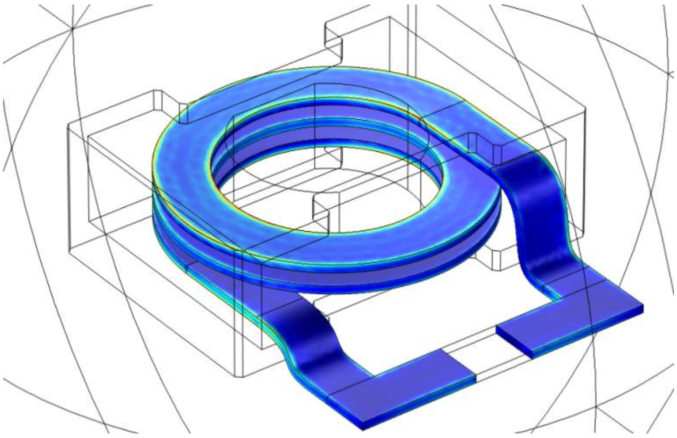

Fig. 3. Inductor winding seen with the core made transparent.

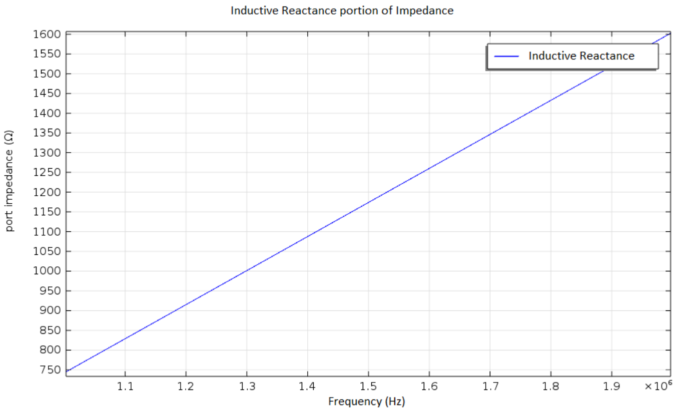

Fig. 4. Graph showing linear relation between inductive reactance and frequency of the alternating current.

IV. RESULT

The older methods of flow measurement using orifice plates and venturi-meter required a lot of preplanning with the pipeline manufacturer and were extremely invasive [2]. Newer methods including the MEMS capacitive sensor were low cost but had nonlinear characteristics and was affected by the type of fluid. The inductor-frequency varying method not only removes problems with type of fluid and linearity but also allows for low cost MEMS manufacture.

Once the inductive reactance vs. frequency graph was plotted, the linearity of the entire system had to be shown. The inductive reactance vs. pressure graph was plotted using the equations given in the design section. From frequency the position was calculated and from the position the force. Finally from the force the pressure was calculated and plotted with respect to the corresponding inductive reactance. Figure 5 shows the relation between inductive reactance and pressure. As seen it is linear. That is the input of the system starting from the pressure exerted by the fluid on the frequency varying spring loaded push button to the output of the system, i.e. the inductive reactance of the inductor coil has a linear relationship between them.

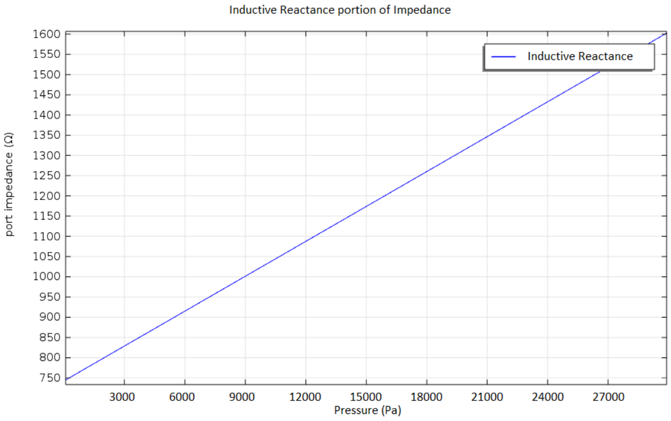

Fig. 5. Graph showing linear relation between inductive reactance and pressure exerted by fluid.

V. CONCLUSION & FUTURE WORK

The inductor flow sensor implemented as shown in the graphs has a clearly linear relation between its input and output. This linearity allows the process of measuring the output relatively easy and slightly cheaper, if we take into account the hardware portion of measuring. But even though this sensor has possible low cost MEMS fabrication and linearity as its features, there is still a lot to be done to improve upon this design. Some of the possible future work is given here.

a) Practical MEMS fabricated hardware implementation of the system.
b) Implementing power producing rotating generator blocks. These blocks use the fluids velocity to generate power, thus allowing the sensor working to be more flexible.
c) Lastly this sensor was designed assuming laminar fluid flow, slight design improvements would allow for flow measurement of all types of flow.

Taking into account the multiple advantages this sensor provides, it could revolutionize the pipeline flow measurement industry with just a few tweaks.

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