

Blood Flow Measurement in Large Blood Vessels using Magnetic Flow Meter

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Abstract:

The magnetic flow meter works on the principle of EMF (Electromotive Force), induced in a moving liquid under the influence of a magnetic field. Magnetic flow meters are popularly used across industries like power generation, oil and gas, material processing and so on. In this article, measurement of blood flow rate in large blood vessels using electromagnetic (EM) flow meter is discussed. The technique is non-invasive since the magnetic field can be generated by coils external to the body and the induced EMF can be measured in a capacitive manner by non-contact electrodes. A possible limitation of the technique is the movement of blood vessels due to the patient's bodily functions like respiration. In this study using a finite element (F.E.) modeling approach (COMSOL Multiphysics tool), an investigation was carried out to check the effect of blood vessel movement on blood flow measurement. The induced EMF and hence the flow meter sensitivity (induced EMF/average velocity), under vessel displaced condition has been compared against that under vessel undisplaced or original condition.

Keywords: Finite Element, Magnetic Flow meter, Induced EMF, Blood Vessel

1. Introduction

Fundamental work on magnetic flow meter was performed by Shercliff [1]. As shown in figure 1, when an ionic fluid like ordinary water flows across a magnetic field an EMF proportional to the velocity is induced across the cross section. The EMF given by $\Phi_1 - \Phi_2$ (potential difference), and divided by the average velocity gives sensitivity of the flow meter. Hence, sensitivity of magnetic flow meter is the calibration factor that relates velocity with induced EMF signal and should ideally be constant under varying conditions. Factors influencing flow meter

performance, like velocity profiles and pipe conductivity were mathematically studied to provide an in-depth understanding of the technique. Use of magnetic flow meter for blood flow measurement was described in several past studies (Wyatt [2], Boccalon [3]). Boccalon [3] studied the theoretical aspects of blood flow measurement using magnetic flow meters and evaluated technical feasibility. However, to the knowledge of authors, the effect of blood vessel movement on flow measurement accuracy has been rarely discussed. The present study focuses on the effect of blood vessel movement on magnetic flow meter sensitivity. In the present study a multiphysics model integrating the physics of laminar fluid flow, electric & magnetic field generation and propagation & structural mechanics has been built using COMSOL Multiphysics tool [4]. The model was used to determine the effect of vessel movement on flow meter sensitivity. The fluid structural interaction (FSI) simulation capability, which integrates fluid flow and structural mechanics calculations, was used to mimic the effect of blood vessel movement on flow meter performance.

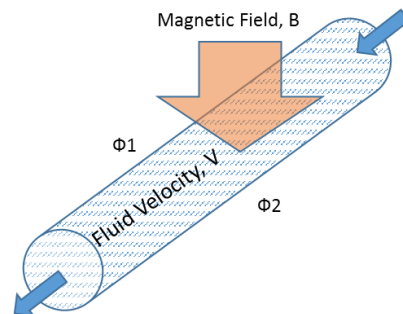
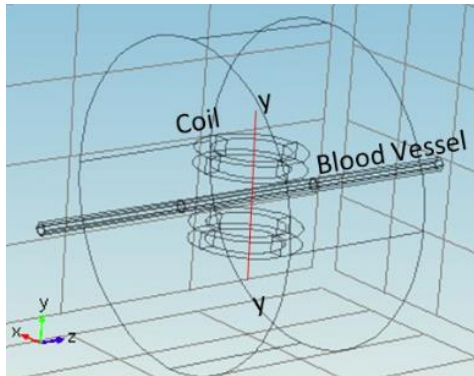


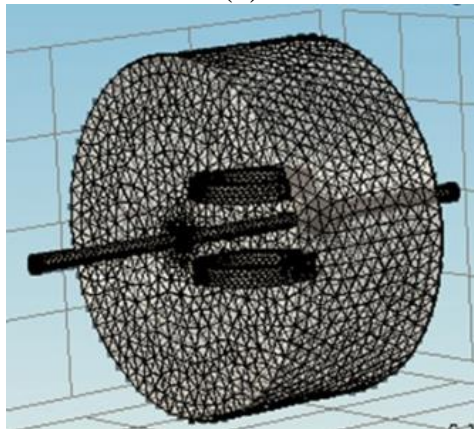
Fig 1: Magnetic Field, B, across pipe with liquid flowing at velocity, V. EMF induced is $\Phi_1 - \Phi_2$.

3. Use of COMSOL Multiphysics

The computational domain or geometry to study vessel movement effect on magnetic flow meter performance is shown in figure 2 (a). The vessel is modeled as a pipe with properties similar to that of the vessel. Figure 2 (b) shows the mesh used to perform the finite element calculations.



(a)



(b)

Fig 2: a) Computational Domain showing blood vessel; b) Domain discretization using tetragonal scheme for F.E. calculations

Modules relevant to the process under investigation were activated in the model. The laminar flow module simulated the fluid (blood) flow through the vessel. The electric and magnetic fields module that calculates the magnetic field generated by the coils (Fig 2a) and the induced EMF as a result of fluid (blood) flow and magnetic field interaction was activated. The structural mechanics module was

used to simulate vessel displacement and interacted with the fluid flow module through the FSI module. The effect of vessel movement on fluid flow and reversely the effect of fluid pressure on the vessel were simulated. Sensitivity of the flow meter under displaced and un-displaced positions of the vessel was compared to determine effect of vessel displacement on flow meter performance.

3.1 Governing Equations

The fluid flow module simulated fluid flow through the pipe using the mass (eq. 1) and momentum conservation (eq. 2) equations:

$$\begin{aligned} \nabla \cdot \mathbf{u} &= 0 & 1. \\ \rho \mathbf{u} \nabla \mathbf{u} &= -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{F} & 2. \end{aligned}$$

Where, \mathbf{u} is velocity vector, p is pressure, ρ is density and μ is dynamic viscosity. Laminar flow was considered in the analysis. \mathbf{F} represents the force acted upon the fluid by the structure and is accounted for in the FSI module. The electric and magnetic field module first calculated the magnetic field generated by the circular coils each on either side of the pipe. A DC current was supplied to both the coils in the same direction, and the magnetic field, $\mathbf{B}(x,y,z)$ within the pipe was calculated using the Ampere's law.

$$\nabla \times \mu_0^{-1} \mu_r^{-1} \mathbf{B} = \mathbf{J} \quad 3.$$

The Electric field induced in the fluid was calculated using

$$\mathbf{J}_i = \sigma \mathbf{E} + \sigma \mathbf{u} \times \mathbf{B} \quad 4.$$

Where \mathbf{E} is the induced electric field generated by the fluid-magnetic field interaction, $\mathbf{u} \times \mathbf{B}$ (Faraday's law). \mathbf{J} is the current induced internally in the fluid and σ is fluid electrical conductivity. Velocity, \mathbf{u} , was obtained from the fluid flow equations, 1 and 2. Electric potential difference, or EMF, induced within the fluid was found by integrating equation (4) over the fluid domain. Hence using COMSOL Multiphysics, EMF induced by the interaction of flow and magnetic fields was computed.

In addition to the above, using the FSI two-way couples module, vessel displacement and its

effect on flow meter performance was simulated. Equation (5), shows how fluidic stresses are transferred onto the vessel and vice versa. While fluidic pressure and stresses impact the structure, structural deformations impact the fluid.

$$\sigma_{solid} \cdot n = \sigma_{fluid} \cdot n \quad 5.$$

3.2 Boundary and Initial Conditions

For the fluid flow calculations, a uniform inlet velocity was imposed across the pipe inlet and ambient pressure was imposed at the outlet. No slip boundary condition ($u = 0$) was imposed at the pipe walls. The velocity value chosen ensured that the fluid flow within the pipe is laminar. The central portion of the pipe, where we are interested, was enclosed in an air domain (Fig 2a). A magnetically insulated boundary condition was imposed at the wall of the air domain. The pipe wall was considered electrically insulated and blood vessel properties were assigned to it. An initial vertical displacement of 0.5 cm was given to the blood vessel towards the top coil, to simulate breathing effects.

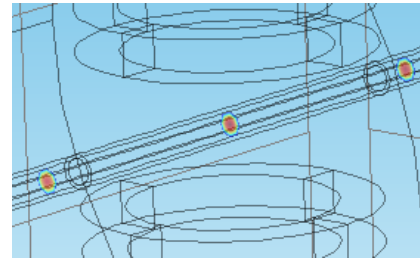
3.3 Computational Method

The magnetic field induced by the powered coils was simulated using the “Multi-turn Coil” option specifying the coil type as being “circular” which requires the current loop to be specified. A stationary or steady state analysis was performed using the segregated solver in 3 steps: segregated step 1 for the electromagnetic fields, step 2 for the structural field and step 3 for the fluid field. The AMS (Auxiliary Maxwell Solver) was used to solve the electromagnetic equations. Step 1 was solved iteratively using the FGMRES solver while steps 2 and 3 used the PARDISO direct solver.

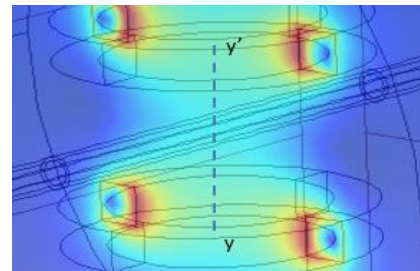
4. Results

Figure 3 (a) shows velocity contour across the pipe cross section, at the center of the coil system. A parabolic profile, to be discussed subsequently (Fig 7), is seen and is typical to laminar flow. Figure 3 (b) shows contour of the magnetic flux density across the pipe cross

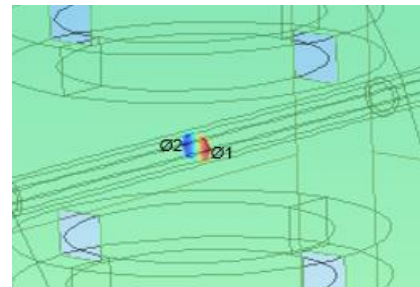
section. The electric potential induced as a result of the flow-magnetic field interaction is seen in figures 3 (c) and (d). While figure 3 (c) shows the potential field across the pipe cross section, figure 3 (d) shows distribution of the field in the lengthwise direction.



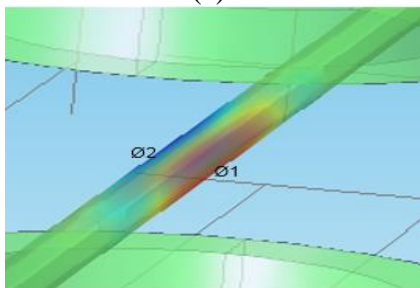
(a)



(b)



(c)



(d)

Fig 3: a) Velocity contours across pipe cross sections, b) Magnetic flux density contour across pipe cross section, c) Induced electric potential across pipe cross section, d) Induced electric potential contour in length wise direction.

A line plot of the potential distribution across the pipe diameter is shown in figure 4. The difference in potential across the diameter ($\Phi_1 - \Phi_2$) gives the induced EMF, which is proportional to the velocity. The induced EMF divided by the velocity gives flow meter sensitivity.

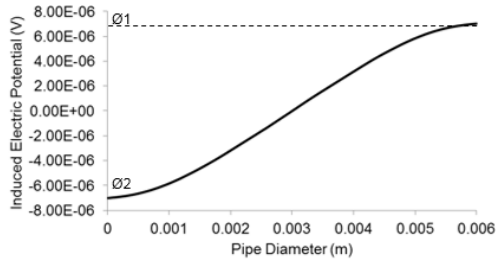


Fig 4: Induced electric potential across pipe or vessel horizontal diameter.

Since the focus of this work is effect of blood vessel displacement on flow meter performance, the vessel was artificially displaced by 0.5 cm upwards, towards the top coil. Displaced position of the vessel is seen in figure 5, which also shows potential distribution across the bent pipe.

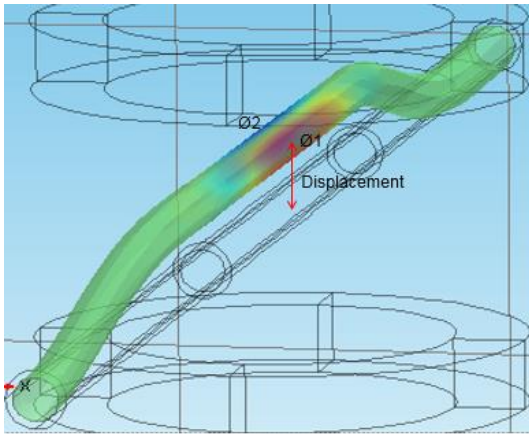


Fig 5: Vessel displacement and induced electric potential distribution.

Comparing sensitivity of the flow meter under displaced and un-displaced (original) pipe conditions (Fig 6), it is seen that there is a 1.5% increase in sensitivity in the displaced pipe

condition. It should be noted that in figure 6, sensitivity has been normalized with respect to the sensitivity under non-displaced condition of the vessel.

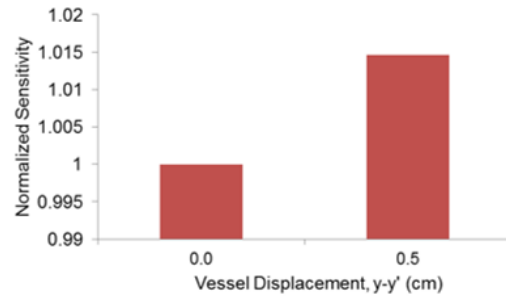


Fig 6: Sensitivity under vessel displaced and un displaced (original) conditions.

The difference could either be due to changes in the velocity profile or in the magnetic field within the vessel. Figure 7 shows that velocity profiles remain the same under the pipe-displaced and non-displaced conditions. Hence, the increase in sensitivity is not due to velocity profile modification due to vessel displacement. Figure 8 shows how the magnetic flux density varies along the vertical direction ($y-y'$ as shown in figure 3b). It is seen that the magnetic flux density within the vessel increases as it moves up towards the top coil. Hence, it is confirmed that increase in sensitivity due to vessel displacement is due to shifting of the vessel to a higher magnetic field zone and not due to velocity profile changes.

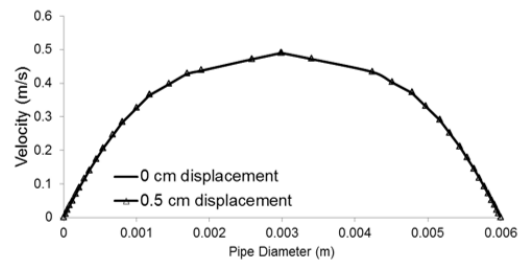


Fig 7: Velocity profiles across pipe diameter for the displaced and non-displaced conditions of the vessel.

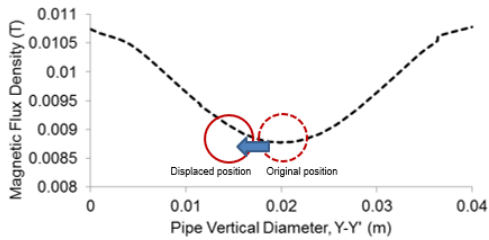


Fig 8: Velocity profiles across pipe diameter for the displaced and un-displaced conditions of the vessel.

5. Discussion

While the magnetic flow meter is an attractive device for blood flow rate measurement, a potential problem could be displacement of the vessel due to bodily functions. Our studies show a 1.5% change in sensitivity due to a 0.5 cm displacement. Vessel displacement of 0.5 cm doesn't substantially change the velocity profile. Perhaps for larger displacements the velocity profile changes as well. While the alteration in sensitivity (1.5% higher) seems negligible, given the globally expected accuracy of magnetic flow meters (within 0.2%), this is a substantial alteration in sensitivity and hence calibration factor. A possible solution could be restricting vessel movement during surgical operations, using restriction devices. Alternately, a breath synchronous magnetic field could be generated, to compensate for alterations in sensitivity due to vessel movement.

6. Conclusion

This work is a useful guide for medical practitioners, interested in employing magnetic flow meters to measure blood flow rate. Further detailed investigations can be performed in this direction, accounting for real conditions like pulsatile blood flow and variations in vessel properties and location within the body. Though the model makes many simplistic assumptions like steady state blood flow, it highlights

capability of COMSOL Multiphysics, in analyzing interaction of diverse physical phenomena like fluid dynamics, structural mechanics and electromagnetics, important for such complex processes.

7. References

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