Electromagnetic flowmeter coil design

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Abstract

Electromagnetic (EM) flowmeters for flow rate measurement of water is a sought after flow measurement device across industry, given their high accuracy and minimal invasiveness. Working on Faraday's law of electromagnetic induction, the EM flowmeter generates a flow-proportional induced electric potential or electromotive force (EMF) signal due to the interaction of a magnetic field with flowing water, water being a conductor of electricity. The strength of the signal depends on the magnitude and distribution of the magnetic flux generated by the electromagnetic coils provided on the pipe surface. In this research work, a 3 dimensional multiphysics model of the electromagnetic flowmeter was developed using the COMSOL multiphysics software, validated with measurements and then used as a tool to modify design of the coils for improving the magnetic flux density and hence the

Introduction

Electromagnetic (EM) flowmeters work on the principal of Faraday's law of electromagnetic induction [1]. The flowmeter primarily comprises a pipe with an inner electrical insulation called liner, a pair of electromagnetic coils for generating the magnetic field within the fluid inside the pipe and a pair of electrodes for measuring the induced EMF. Based on a pre-established calibration curve between the induced EMF and the flowrate, the flowrate is estimated. Proper design of the magnetic coils is crucial because the design determines the strength and distribution of the magnetic field which influences the strength of the induced EMF signal. To evaluate coil design modifications for possible improvement in performance a high-fidelity physics-based tool to predict performance is needed. Researchers have generally adopted the method of weight function to model EM flowmeter performance in 2 dimensions [2]. However, such models assume a uniform magnetic field which is not the case in the real flowmeter. In this paper, a 3D multiphysics model developed to simulate working of the electromagnetic flowmeter is described. The model was validated with measurements and then used to evaluate coil designs for the strongest magnetic field and consequently the strongest EMF signal.

Keywords

Electromagnetic flowmeter, multiphysics, modeling, electromagnetic coils, induced EMF

Simulation Model

Modeling methods

Figure 1A below depicts the working of the EM flowmeter and Figure 1B shows the construction, simplified for understanding. A magnetic field generated by a pair of coils above and below the pipe, is induced within a pipe through which water flows. Water being an electrical conductor, an electric potential or electromotive force (EMF) is induced within it, as per Faraday's law of electromagnetic induction. The induced EMF is proportional to the fluid flowrate and on the basis of it, the flowrate is estimated.

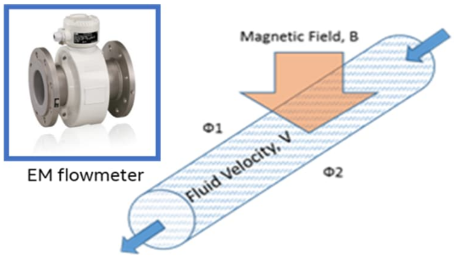

Fig 1A

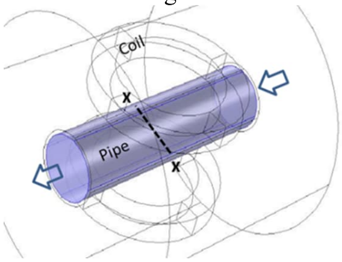

Fig 1B

Fig1A: Working principal behind EM flowmeter; Fig 1B: Simplistic depiction of EM flowmeter construction.

The multiphysics model of the EM flowmeter comprises the modules of computational fluid dynamics (CFD) and the magnetic and electric fields in COMSOL. The CFD module computes the fluid or velocity field within the pipe while the magnetic and electric fields module computes the magnetic flux density distribution and the induced electric potential resulting from the interaction between the flow and magnetic fields. The boundary conditions of the model are the inlet velocity and the outlet pressure (gauge pressure = 0) for the fluid flow computation. The walls are prescribed a no-slip or zero velocity condition. The coils are prescribed a fixed current for the generation of the magnetic field. The air around the flowmeter is modeled and the magnetic and electric insulation boundary condition is imposed on the air boundary.

Following are the governing equations solved by the code:

For fluid dynamics simulation:

Continuity equation (ensuring conservation of mass)

$\nabla.u=0$ eq. 1

where u is the velocity (representative of velocities in all dimensions)

Momentum equation (ensures conservation of momentum)

$\rho u \nabla u = -\nabla p + \mu \nabla^2 u$ eq. 2

ρ is density, μ is dynamic viscosity. For simplicity laminar flow equation is shown above. In reality turbulent flow equations using the RANS (Reynolds average naviers stokes) equations are solved.

For magnetic and electric field simulation:

Ampere's law (solves the magnetic field distribution generated by the coils)

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

μ_0 is vacuum permeability, μ_r is relative permeability.

Current conservation (conserves current)

$\nabla.J = 0$ eq. 4

J is the current density.

Lorentz term (solves Faraday's law of electromagnetic induction in liquids)

$J_i = \sigma E + \sigma u \times B$ eq. 5

B is the magnetic flux density. Interaction between B and the velocity u, induces the electric field E. We see that E is proportional to velocity, u and can be used to estimate u.

Model Results

The primary parameters of interest are the fluid velocity, magnetic flux and induced electric potential. Figure 2A, below shows the fluid velocity field within the central traverse section of the pipe. Figure 2B shows the magnetic flux density distribution across the same section. The interaction between the fluid velocity and the magnetic field yields the induced electric field or the electromotive force. The distribution of the induced electric field is shown in figure 2C. The difference between the fields across the diameter is the induced EMF which is measured by electrodes, not shown here. The induced EMF is proportional to the fluid velocity averaged over the cross section, u_{avg}. The ratio of the EMF/u_{avg} is termed the sensitivity of the flowmeter which is also the calibration factor of the flowmeter. A high sensitivity is desired for the flowmeter to be able to measure low flowrates.

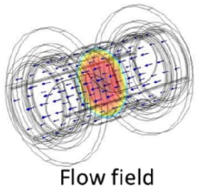

Fig 2A

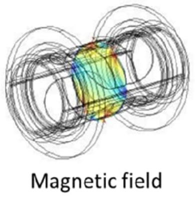

Fig 2B

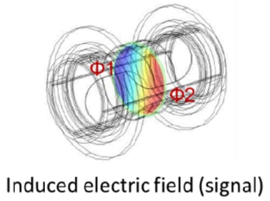

Fig 2C

Fig 2A: Computed flow field; Fig 2B: Computed magnetic flux; Fig 2C: Computed induced electric field across the central cross section of the flowmeter.

Models were developed to simulate a variety of flowmeters differing in size and make.

Model Validation

After developing the models, the results were compared with measurements to check the accuracy of the models. Figure 3 below compares sensitivites computed by the model and those measured in the tests. The close agreement between the computed and measured values indicate accuracy and reliability of the model.

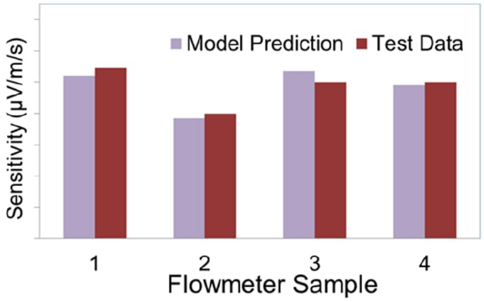

Fig 3

Fig 3: Comparing computed and measured sensitivity of sample flowmeters.

Validation of the model instilled confidence in the modeling approach for predicting EM flowmeter performance. Hence the model was used with confidence in evaluating the benefits of component modification like the coils.

Coil design modification

Using the validated model, various design modifications of the coils were evaluated for possible improvement in magnetic field strength and hence the EMF signal strength. Figure 4A shows the original or elliptical coil, while figure 4B shows the optimized coil design arrived at after several iterations. The optimized coil is almost rectangular in shape with rounded corners.

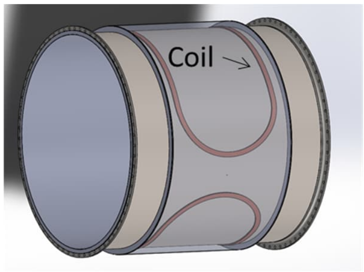

Fig 4A

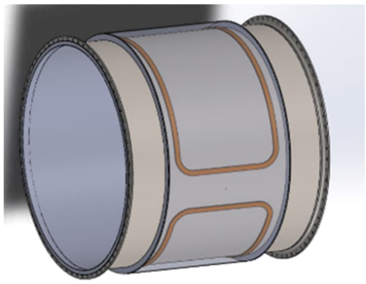

Fig 4B

Figure 4A: Original or elliptical design of the coil; 4B: Final or optimized coil design, rectangular with rounded corners.

Figure 5A below compares the magnetic flux density across the pipe diameter generated by the original and optimized coils. It is seen that the optimized coil generates a field which is almost 18% larger than the one generated by the original coil at the ends of the pipe diameter. Figure 5B shows contours of the magnetic flux generated by the rectangular coil. It is seen that there is an enhancement of the field near the electrodes or at the diameter extremes where the electrodes are located. This is expected to improve the signal strength of the flowmeter.

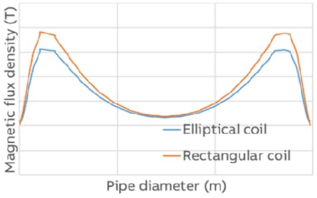

Fig 5A

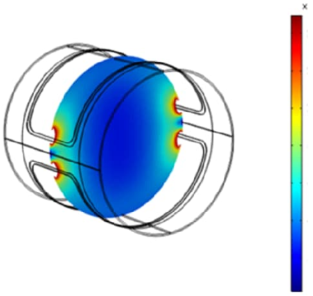

Fig 5B

Fig 5A: Comparison between magnetic flux densities generated by the elliptical (original) and rectangular (optimized) coils. Fig 5B: Magnetic flux densities across the central pipe cross section generated by the optimized coil.

Design fabrication and verification

After evaluation of the optimized coil design using the model, the design was selected for fabrication and testing. Figure 6 below shows the fabricated optimized coil, rectangular in shape with rounded corners. The coil was mounted in the flowmeter, which was subsequently tested in the rig. A 12% increase in signal strength compared to that obtained from the original design was measured. Hence the superior performance of the optimized coil revealed by the model was confirmed by real testing.

Fig 6

Fig 6: Fabricated optimized coil subjected to testing.

Conclusions

The multiphysics model of the EM flowmeter validated by testing, proved to be a high-fidelity tool for evaluating design modifications for improving flowmeter performance. The model has already been used to evaluate several ideas other than coil modification, for improving performance of the flowmeter, not shown here. In future the model will continue to be used for evaluating new ideas for taking flowmeter performance to the next level.

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[2] M Karamifard, M Kazeminejad, A Maghsoodloo. “Design and Simulation of Electromagnetic Flow meter for Circular Pipe Type.” *World Academy of Science, Engineering and Technology*. Pg. 863-878. 2011.