Validation of a Multi-physics Simulation Approach for Insertion Electromagnetic Flowmeter Design Application

by A. Guada, S. Rogers

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Motivation

Markets

Insertion electromagnetic flowmeters are preferred for a variety of applications where:

- moving parts are not desired due to the presence of debris.
- durability is important.
- non-disruptive installation is necessary.
Motivation

Performance

Within these market places, there is still a need of higher precision insertion electromagnetic flowmeters.
Background

Facts

- Generally, electromagnetic flowmeters (EMFM) are inline devices.
- Inline EMFMs are very accurate instruments due to nature of their designs, in comparison to insertion EMFMs.

Inline EMFM  Insertion EMFM
Principle

EMFMs measure an induced voltage as a result of the interaction of an electromagnetic field with a moving conductive fluid.
Virtual Current Density

The current density is best understood by assuming a unit current (1A) travels from one electrode to the other, even though in reality the current is near zero.
Voltage Output

The resultant electromagnetic field generates a voltage output that is “proportional” to flowrate of the conductive fluid.
Inline Vs. Insertion EMFM

Magnetic Field

Current Density

Voltage Signal Distribution
Electromagnetic Hydrodynamics

Voltage Output

The voltage generated as a response to a conductive moving fluid is defined as

$$V_L = \int \int \int_{\Omega} J \times \langle B \rangle \cdot \langle U \rangle \, d\Omega,$$

where the time-averaged velocity field $\langle U \rangle$ interacts with a time-averaged magnetic field $\langle B \rangle$, accounting for virtual current density distribution $J_v$ within fluid volume $\Omega$. 
Virtual Current Density

According to the Ohm’s law, the current density is defined as

\[ J = \sigma \left( \langle E \rangle + \langle U \rangle \times \langle B \rangle \right), \]

where the conductivity \( \sigma \) of the moving fluid creates a time-averaged electric field \( \langle E \rangle \). With a set of electrodes with different potential, a current

\[ I_L = \int \int_S \sigma \left( \langle E \rangle + \langle U \rangle \times \langle B \rangle \right) dS, \]

flows from one electrode to the other, where \( S \) is the surface of the electrodes. Finally, the virtual current density is determined as

\[ J_v = \frac{J}{I_L}. \]
Device-under-test (DUT)

The insertion electromagnetic flowmeter below was tested in a 4in-SCH-40-PVC pipe.
Test Case

Insertion Depth Cases

The insertion EMFM was tested at the following insertion depths.

0.1D 0.5D
Experimental Setup
An insertion electromagnetic flowmeter was installed and tested in the flow lab below.
Numerical Model

- Infolytica’s finite element method (FEM) code MagNet and ElecNet were utilized to simulate both the steady-state magnetic and current density fields.
- For Star-CCM+, Steady-state Reynolds-averaged Navier-Stokes (SRANS) and Embedded Detached-eddy Simulation (EDES) were used to simulate the raw voltage signal in response to several flow rates.
Turbulence Modeling

Steady-state RANS

- A variety of RANS models were used e.g. Spalart-Allmaras (S-A), Shear-stress Transport (SST), Elliptical Blending (EB) K-epsilon.
- A CFD domain was sized accordingly in order to provide enough run to develop a fully-developed velocity profile.
- Segregated solver with the second-order upwind scheme.
- Convergence criteria $\leq 0.0001$. 

Steady-state RANS
Turbulence Modeling

Embedded Detached-eddy Simulation

- Fully-developed velocity profiles, from preceding simulation using SRANS-SST model, were prescribed to the inlet of a CFD domain.
- Synthetic-eddy method (SEM) was applied to the inlet boundary conditions with a turbulence intensity $I_T = 3.0\%$ and a turbulence length scale $L_T = \delta/4$.
- $3D$ upstream and $2D$ downstream of zone of interest were used. $D =$ pipe inside diameter.
- Trimmer mesh type with cell sizes $\Delta = \delta/10$ and with prims layer accommodating $y^+ < 1$.
- Improved Delay-detached-eddy Simulation (IDDES)/S-A formulation.
- Segregated solver with hybrid second-order upwind/bounded central-differencing scheme and second-order temporal discretization.
- Convergence criteria $\leq 0.0001$.
- CFL $< 1$. 
0.1D-insertion Depth

Steady-state RANS

Overall, SRANS performed the best within the pipe velocity $V_{avg} > 2\text{ft/s}$ range in comparison to the experimental data (EXP). On the other hand, SRANS dramatically disagreed with EXP within $V_{avg} < 2\text{ft/s}$ range.
0.5D-insertion Depth

**Steady-state RANS**

In the following case, the agreement between EXP and SRANS is significantly better than the one observed in the previous test scenario. Notice that the lower disagreement starts from \( V_{avg} < 1 \text{ft/s} \).
Discussion

Steady-state RANS

- No significant advantage was observed between one turbulence model and the other.

- Comparing both cases, SRANS over-predicted the voltage output at lower pipe velocities.
  - The higher energy transfer between scales that occurs at low velocities is responsible for the disagreement with EXP.
  - This can be seen with the difference of performance when the sensor is placed near the wall pipe and center flow velocities.

- Despite the disagreements in the results, SRANS performance is not a surprise.
  - RANS formulations are not efficient at resolving flow mixing away from the wall.
SRANS Vs. EDES

Therefore, there is sufficient justifications to use a higher turbulence modeling approach.
0.1D-insertion Depth

**SRANS Vs. EDES**

The EDES was capable of producing results similar to the experimental data.

![Graph showing comparison between SRANS and EDES](image_url)
Discussion

SRANS Vs. EDES

The result implies that the EDES approach used in this study was sufficient to show large deviation between the voltage generated with respect to flowrate.
Conclusion

- The multi-physics approach used in this study was validated using experimental data and a high turbulence modeling approach.

- The integration of MagNet, ElecNet and Star-CCM+ was successful.
  - Star-CCM+ allows easy-ways to import volume mesh data from other software into the CFD domain, and perform the required calculations.
Conclusion

- The need of higher turbulence approach beyond SRANS was demonstrated.
  - SRANS is capable of predicting linearity features of an insertion EMFM.
  - Any related large-eddy simulation (LES) approach is advised when precision is required.
- EDES potentially offers significant advantages over SRANS e.g. linearity, signal strength and noise predictions.
Thank You!
References


