Making sense

Designing more accurate and robust sensors through system and multiphysics simulation

ROLF DISSELNKOETTER, JÖRG GEBHARDT, ROSTYSLAV TYKHONYUK, HOLGER NEUBERT – **Instrumentation is a critical element of many of ABB's businesses. To keep pace with rapidly evolving requirements, the company is taking a leading role in sensor technology research, seeking to develop new sensing technologies, decrease sensor footprint, fulfill new standards and develop innovative applications. With these goals in mind, ABB is using system and multiphysics simulation to successfully develop more accurate and robust sensors.**

1 von Mises stress distribution caused by an external static torque

Deformations exaggerated by a factor of 1,000

Sensor development is quite often characterized by high requirements in accuracy. In fact, some applications require accuracies of up to 0.1 to 0.05 percent of the measured value.

Sensor technologies often show nontrivial system-level effects, eg, because of design details or the number of components whose behavior influences the measurement chain. Internal and external influences (eg, thermomechanical, chemical, electromagnetic crosstalk) may cause unwanted drift of gain, phase and offset, and may deteriorate the accuracy and stability of the measurement signals.

Full system simulations or multidomain physical simulations can be used to avoid cumbersome tests on a number of physical prototypes, and to obtain a reliable high-accuracy prediction of device performance. Sensor design, therefore, is a prime example of model-based mechatronics development, described, eg, in [1]. Examples of these two simulation cases follow.

Title picture
The FCB 350 Coriolis flowmeter (DN25)

Coriolis flowmeters

A Coriolis sensor is a system with strongly interacting components. When the drive unit is supplying an AC current to an actuator on the flow tubes, they will vibrate. Due to the Coriolis effect, fluid flow through the tubes will generate small phase shifts between the vibrations at different locations in the mechanical system. This is detected by means of two vibration sensors placed at different locations. The electronics evaluates the phase shift between the two sensor signals and uses their amplitude to control the drive current.

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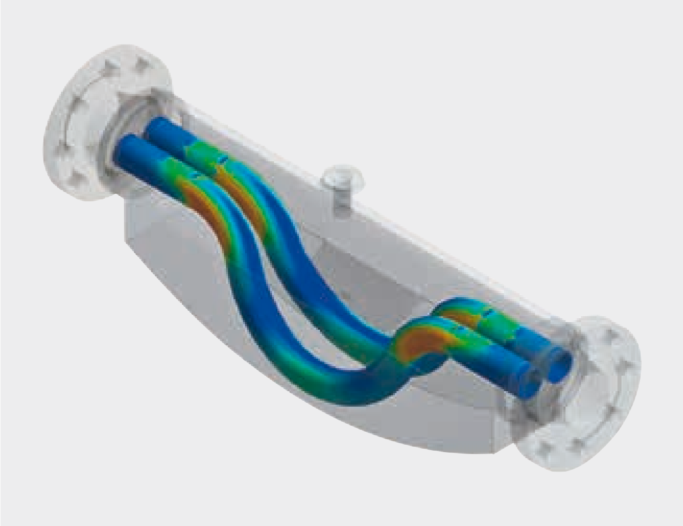
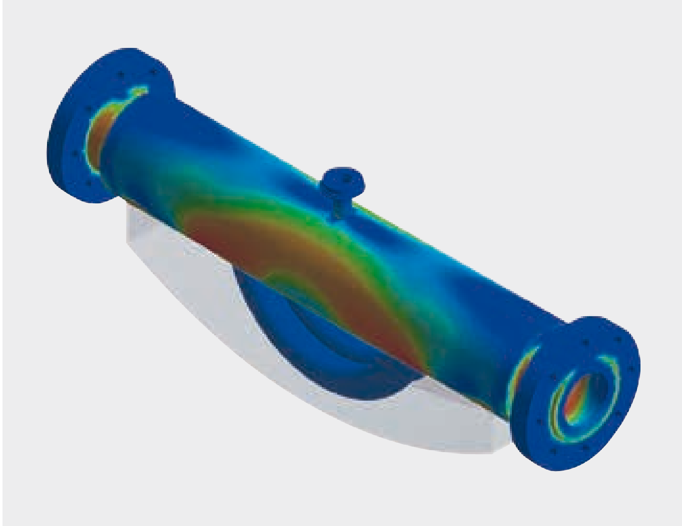
Not only is profound theoretical know-how required in the design of Coriolis flowmeters, but the R&D methodology must be highly efficient. It has to enable the design of complete product lines,



2a Operational eigenmode: deformations and stress distribution



2b Stress distribution for the lowest eigenmode of the device´s housing

and of customer-specific product variations. Quantitative design criteria, which can be operationalized in virtual and experimental tests, form the basis of excellent development results.

Sensitivity and cross-sensitivity
Exact numerical prediction of flow sensitivity has two important purposes: First, it enables analysis of external influences according to their actual effect on the measurement process, and in this way minimizes unwanted cross-sensitivities and optimizes the design. Second, the same range of output signals is common to the entire range of meter sizes, and thus optimizes the signal processing algorithms.

Mechanical robustness and dynamic stability
All measurement signals generated by the device must be stable under a number of inevitable and potentially erratic environmental influences.

An important performance and device stability criterion, which can be efficiently tested by simulations, is given by density measurement under various external loads. As a first calculation step, a typical worst-case load is applied to the device. ➔ 1 shows the nonlinear response of the structure for a specific external load. The result of this step is also used to determine mechanical device robustness.

In a second step, eigenfrequencies of the system are calculated, as shown in ➔ 2a. For a design to pass this test, it is important that load-induced frequency shifts do not violate the accuracy requirements of the device.

Further, a decoupling of the operational vibrations from the outer shell of the device is important. By choosing special design parameters, the operation mode will be well separated from the modes of the outer surface. An example of the latter is shown in ➔ 2b.

Robust design for performance reliability
For high-quality flow measurement, the main variable to be controlled is the “zero phase,” the integral measure for the influence of superimposed manufacturing tolerances and asymmetries, which lead to a nonzero signal without flow. It is particularly challenging to reduce time-dependent physical influences on the zero phase, as this can lead to errors in the measurement result, which cannot be compensated. External damping elements may touch the device at any position on its outer hull, which is vibrating due to the meter´s operating principle. In such a case, energy is extracted at that position, leading to a low-amplitude change in the traveling wave structure in the device. The internal and external mechanical setup of a Coriolis meter must be carefully chosen to keep this influence small, in particular with respect to the consequences on the motion of the sensor tubes and signal pickups.

Algorithms have been developed that allow a highly efficient calculation of zero phases as a function of local damping –

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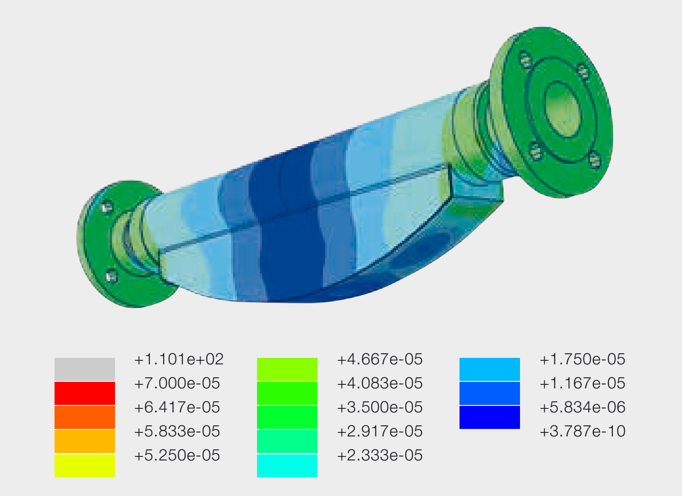
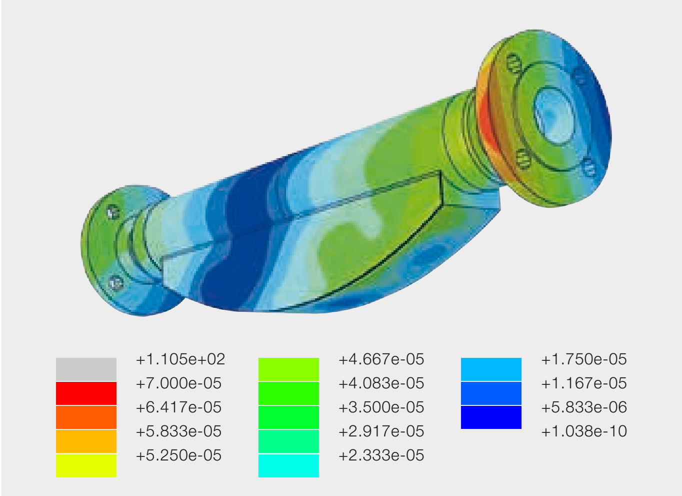
3 Contour plots of zero phases (in degrees), induced by a damper of given constant strength, as a function of damper location



3a In absence of preloads (no external static forces applied)



3b Under a strong external static load (axial torque)

ie, damping strength and damper location. This is a special numeric challenge as well, since the phases to be calculated are exceptionally small – in the range of 10^{-5} degrees.

➔ 3a shows a contour plot of induced zero phases as a function of damper location for a given constant damper strength. The calculation result can be compared with the allowed limit of zero phases for the given flowmeter. ➔ 3b shows the same situation when the system is put under a strong axial torque load. The result shows that, for this design, the zero phase remains stable at a very low value even for strong external influences.

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Finally, representative criteria have been selected that are efficient to use and reliably represent stable zero-phase behavior for the ABB CoriolisMaster product design. For a number of Coriolis meters, virtual drop-impact (ie, crash) tests are performed [2] via finite-element calculations with explicit time integration.

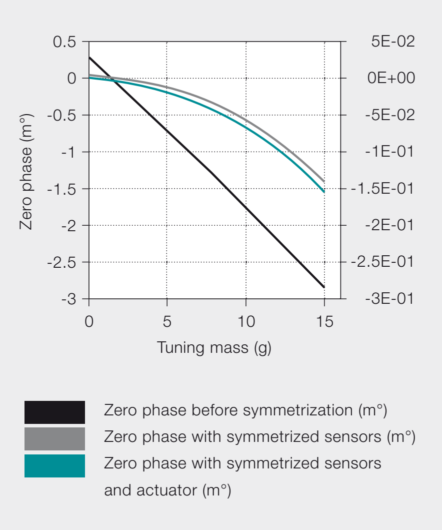
To arrive at a robust, low-cost design, sensitivity analyses with respect to inevitable manufacturing tolerances are performed. Flowmeter production can thus be tailored to achieve the highest customer value. In a robust design, the tolerances have less influence on performance [3] ➔ 4.

Magnetic design in a system context

The couplings in a Coriolis sensor, which as mentioned has strongly interacting components, are indicated with black arrows in ➔ 5. The included actuator and vibration sensors are based on the voice coil principle. This is comprised of a permanent magnet, a soft magnetic flux concentrator and a movable coil in the magnetic air gap. The force between the magnet and the actuator coil generates the vibrations that are measured through the voltage induced in the sensor coils.

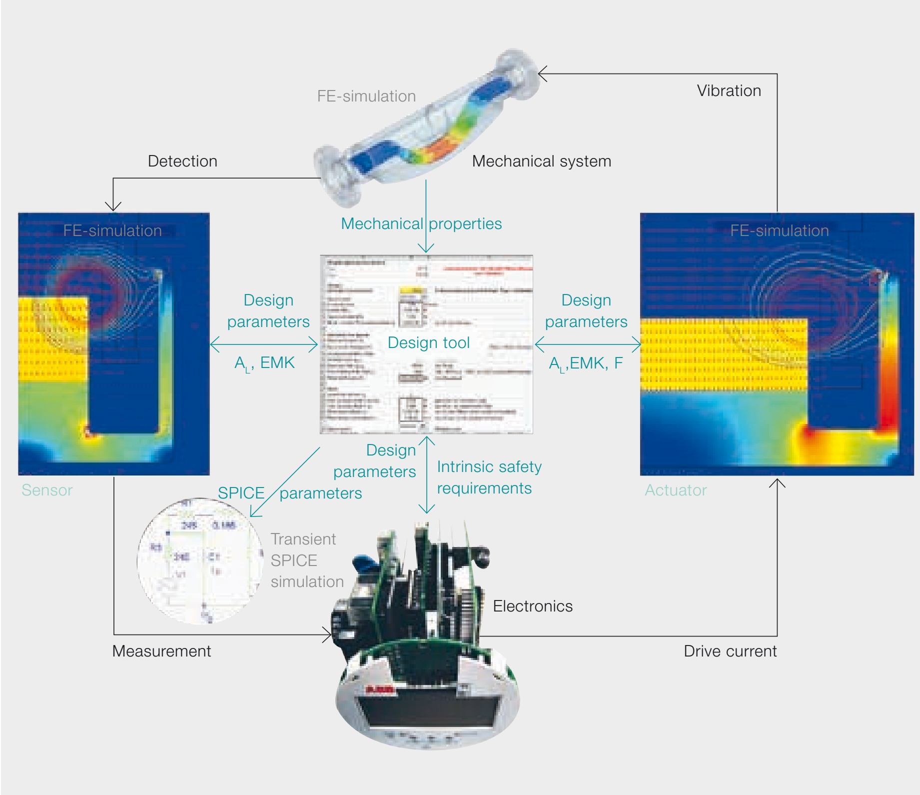
When designing and optimizing the magnetic components, the complete chain of interacting parts must be considered. The required sensitivities of the actuator and sensors, for example, depend on each other and on properties of the mechanical and electronic subsystems. In addition, boundary conditions like the maximum weight and size of the mag-

4 Zero phase vs. tuning mass



For the gray and green curves, the right y-axis, which is scaled up by a factor of 10, applies. The symmetrized design has a zero point that is much more stable under mass differences between the twin tubes.

5 Magnetic and electronic design process for the sensor-/actuator system



netic parts, and limitations of the electric impedances and signal amplitudes from intrinsic safety requirements, must be taken into account.

This is ensured by using a spreadsheet-based design tool, which enables collection and matching of the magnetic, electronic and mechanical data required. The tool provides an interface to the FE (finite-element) models of the magnetic components by exchanging design parameters and the resulting electromagnetic characteristics. Further, it gathers the results of the mechanical simulation and includes a simplified model of the drive circuitry. During the parameter optimization it monitors compliance with the design goals and boundary conditions by indicating any deviations. Thus, the design of magnetic components and drive circuitry can be developed in an iterative process. The tool can also output the parameters of a basic equivalent-circuit SPICE (simulation program with integrated circuit emphasis) model for the transient simulation of the drive, actuator and mechanical system. ABB has already designed several new Coriolis sensors using this tool and the implemented design process.

To arrive at a robust, low-cost design, sensitivity analyses with respect to inevitable manufacturing tolerances are performed.

Electromagnetic sensors

Common electromagnetic sensors include current transformers (CT), position and proximity sensors. Although several simulation tools are suited for investigating such systems, special modeling techniques and solver settings are often required to obtain stable and efficient calculations and accurate results. Further, a reasonable compromise between model complexity and accuracy needs to be made.

Typical challenges with sensor simulation include:
- Complex 3-D geometry that includes details over a wide size range
- Nonlinear effects
- Hysteresis
- Transient behavior
- Cross-talk
- Coupling of physical effects that react on different time scales (eg, electrical and thermal)

In 2009 ABB began collaborating with the Dresden University of Technology to develop FE modeling techniques for electromagnetic sensors, which are applicable in different development projects. The focus is on 3-D models with coupled parameters (multiphysics models).

Sample system

→ 6 shows a geometry model that has been used in the investigations. Although this is not a real design, it has the typical properties of some types of current sensors.

It is a nonsymmetric 3-D model of a CT with a primary busbar and a secondary winding, which is split into two coils. The magnetic core has two different types of air gaps. The dimensions of the paramet-

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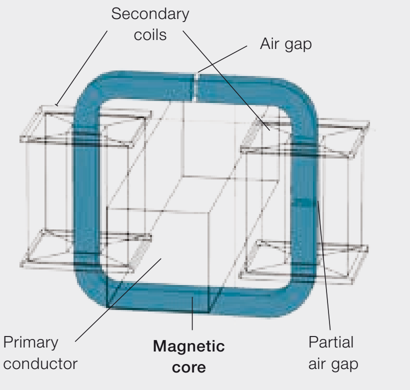
6 Geometry of a transformer model



ric model can be modified, and it can be extended with a flux sensor in one of the gaps and with electric circuitry to form a closed-loop current sensor.

Based on this design, various model versions were developed to investigate different physical aspects. They enable modeling of the phenomena and their properties either separately or in combination.

Model features

The model in ➔ 6 presents several challenges: It is 3-D, nonsymmetric (ie, cannot be reduced to a subgeometry with suitable boundary conditions) and contains small details (ie, air gaps) in a large structure. These air gaps strongly influence the stray-field distribution and the properties of the sensor. However, without optimized geometry meshing they will lead to a large number of finite elements and long calculation times.

Additional features implemented in the models thus far are highlighted in ➔ 7. This list shows that, in a real sensor, there may be many physical effects and couplings. Which of these need to be considered in the analysis depends on the specific problem.

Results

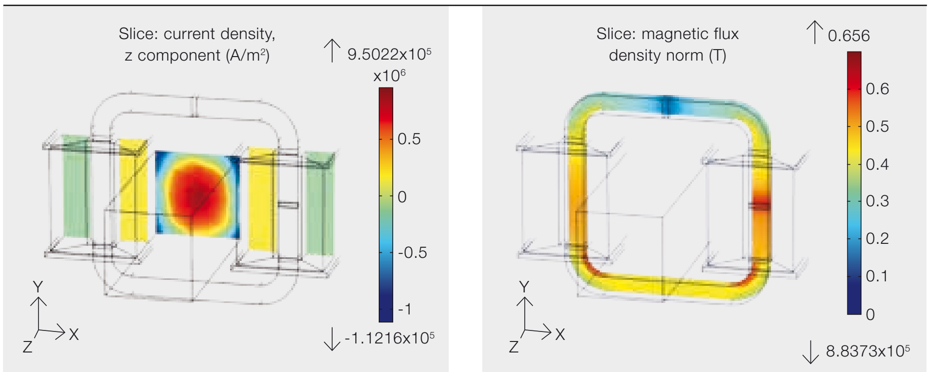
Good progress has already been made on the models [4, 5]. ➔ 8 shows results obtained on a model version with a bulk copper busbar and a FeSi-based core material with a nonlinear magnetic characteristic. It is assumed to be electrically nonconductive. Therefore, there are no electric core losses and a nonlaminated core model can be made. The FE model is coupled to SPICE circuit models with a sinusoidal current source at the primary side and a load resistor at the secondary winding, which has N_{sec} loops. The loss distribution is calculated and used as input to the thermal simulation, which then yields the temperature distribution. Electric conduction is temperature dependent. Because of the nonlinear core characteristic and the coupling to a circuit model, transient simulation is required.

7 Electromagnetic sensor model features

- Nonlinear, anhysteretic magnetic characteristic H(B) of the core material. An analytic formulation has been chosen for best numerical stability.
- "Wire-bound" secondary current distribution in the coils modeled with eight prismatic bodies. Copper resistance is temperature dependent.
- Models are suited for transient simulation.
- Coupling with integrated SPICE circuit models (eg, current source, secondary load, closed-loop operation with additional flux-sensor).
- Induced eddy currents in the primary busbar leading to additional losses and to an inhomogeneous current-density distribution from the skin effect. The air gaps will cause sensitivity with respect to magnetic stray fields and the current distribution.
- Calculation of the conduction loss densities in the primary and secondary windings.
- Explicit and analytical modeling of laminated (stacked or strip-wound) cores.
- Dynamic hysteresis and electric loss distribution from eddy currents in the magnetic core.
- Integrated thermal model calculating the temperature distribution from the electric losses in the windings and the magnetic core. Temperature drift of electrical conductivities is considered in a closed-loop iteration process, controlled with an external program.

Special modeling techniques and solver settings are often required to obtain stable and efficient calculations and accurate results.

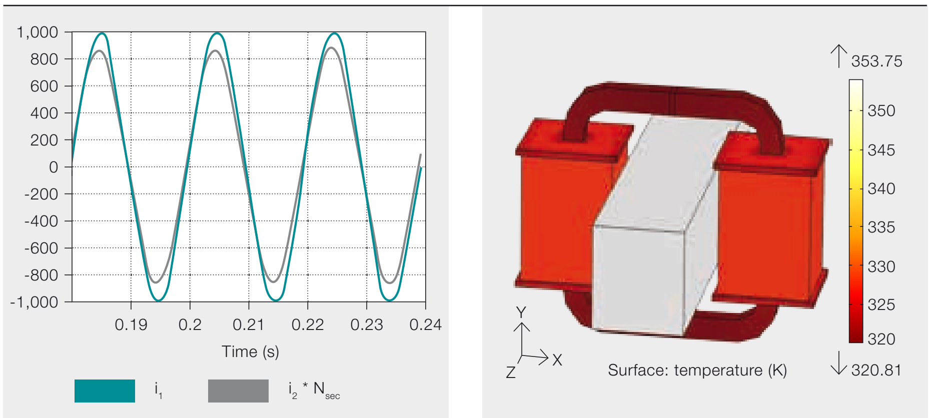
8 Current and magnetic flux-density distribution



8a Instantaneous current-density distribution (z-component) with skin effect in the primary conductor

8b Respective instantaneous magnetic flux-density distribution (absolute value) in the center plane of the transformer core

9 Current signals and temperature distribution



9a Primary and normalized secondary current showing an imperfect transformer coupling

9b Resulting stationary temperature distribution at the surfaces of the solids

➔ 8 shows the resulting current-density distribution in the conductors at a specific point in time. Skin effect is visible and it can be seen that a reverse current is even flowing at the center of the busbar. The respective asymmetric core flux-density distribution is influenced by both the current distribution and the air gaps.

➔ 9 shows the current signals, which do not match well and thus indicate an imperfect transformer coupling due to the air gaps. Further, the stationary temperature distribution shows the effect of the electrical conduction losses.

As research continues, ABB and its academic partners will focus on improved laminated-core models for higher frequencies, automatic calibration of the nonlinear magnetic characteristic, the implementation of different coil winding shapes, further improved SPICE modeling and experimental model validation.

Transforming technology for customers

System and multiphysics simulations are essential to gain a deeper understanding of sensor performance. Devices like Coriolis flowmeters – which, in addition to the standard physical quality testing, have passed a carefully chosen set of virtual tests – offer customers enhanced value through increased accuracy and robustness, as well as optimized material use.

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