Absolute and relative phases in twin-tube structures and performance criteria for Coriolis meters

Jörg Gebhardt

ABB Corporate Research Center Germany, Ladenburg

Abstract: The main technological problem in Coriolis meter design is to achieve robust flow and density measurement signals. In this note, it is demonstrated that Abaqus is a well suited tool for implementation of related design performance criteria. It has played a major role in the development process of the new ABB Coriolis Master FCB330/350.

1. Introduction

The measurement value of a Coriolis flow meter is expected to give information on the mass flow inside of a tube to an accuracy of about 0.1%. This, in particular, poses high requirements on meter design and manufacturing tolerances.

The well-known (see, e.g., Baker, 2000) Coriolis measurement element consists of a flow tube which is excited by some actuator to oscillate transversally, similar to a violin string. When there is no flow inside the tube, all points of the structure oscillate in phase, e.g. have the zero-crossings of their motion at the same time. In case of flow inside the tube, a characteristic tumbling of the motion sets in, leading to measurable phase shifts along the flow tube. The latter are, to a usually high accuracy, proportional to the flow of inert mass. For typical metal tube examples, phase shifts per kg/s flow are about 50 m°. For typical meter frequencies of approximately 1 kHz, this means a time shift of 139 ns. The accuracy requirements, therefore, implies measurements which are exact to less than 1 ns.

So, modeling and simulation in product development face a considerable challenge when aiming to predict meter performance. In particular, sensitivity analyses are required for estimation of allowed manufacturing tolerances. This has a big impact on the device´s cost structure.

2. Modeling

2.1 Finite-element model setup

ABB´s CoriolisMaster FCB330/350 is a twin tube device, which means that two flow tubes are excited synchronously at their midpoints, and the signals are picked up from their relative deflection at sensor positions upstream and downstream, at equal distances from the actuator.

The models reported in this paper describe a concept demonstrator for the product, which was equipped with specific tuning opportunities for performance investigations.

The system considered for simulation, together with a suitable notation for the parts, is given in Figure 1. (The housing of the device has been omitted in the picture, but was included in the calculations.)

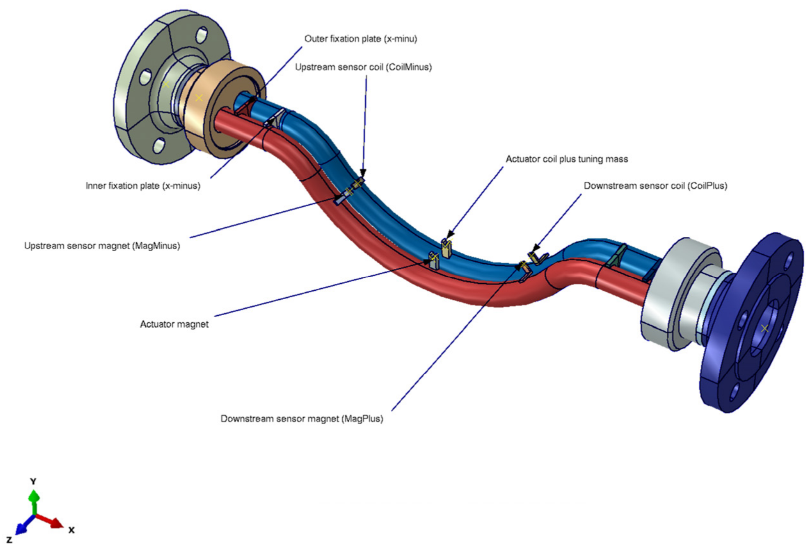

Figure 1. System view of the DN50-model with notation for the parts, which is sometimes important when discussing symmetry aspects. (Outer housing is omitted in the picture, but was included in the calculations.)

The meter has two important symmetries: First, the structure shows an upstream-downstream, $\pm x$ – symmetry, which is usually fairly well realized in manufacturing, but possibly broken by external influences and mounting/boundary conditions. Indeed, in our case we assume basically free boundary conditions, but apply a damper at the right process connection. Second, there is a $\pm z$ – Symmetry which is usually slightly broken by small mass differences between magnets and coils at the actuator and sensor positions. In the case of our model, the actuator coil position is additionally equipped with a tunable mass.

2.2 Analysis procedures and calculation cases

We compute complex eigenmodes (Abaqus User's Manual, 2012) of the mechanical structure including a localized damper and, in part, Rayleigh damping for the material. In some cases, an additional calculation of the driven steady state has been carried out. In all these cases the zero phases were numerically identical to those determined in the complex eigenfrequency calculation. Runtime of the jobs is about 500 s on a 12-core workstation.

2.3 Materials

The solid and shell parts of the system consist all of stainless steel. Rayleigh damping, additionally, has been defined by α=0 and β=10^{-8} s, which, e.g. for an eigenmode at ν=420 Hz, produces a modal quality factor of

$$Q = \frac{1}{\frac{\alpha}{\omega} + \beta\omega} = \frac{1}{2\pi \cdot 420\,\mathrm{Hz} \cdot 10^{-8}\,\mathrm{s}} \approx 38000$$

2.4 Element choice

The device consists of stainless steel parts which are represented by solid or shell (in case of the flow tube) elements. Magnets and coils of the actuator and the sensors are represented by point masses. Their moments of inertia have not been included in the model. They may have an influence on absolute values of zero phases, but it is assumed that they do not play a role in the relative influence of tolerances, which is the topic of the recent study. The geometric modeling of actuator and sensor is given in Figure 2.

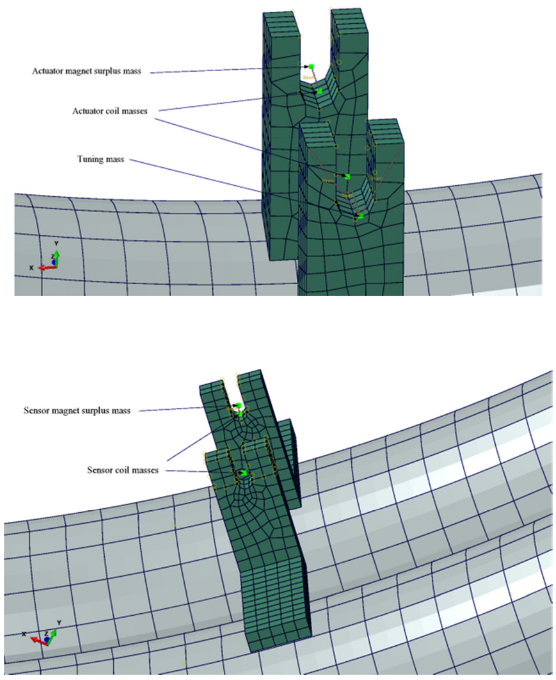

Figure 2. Geometric models of actuator (above) and sensor (below) via mass points. Beam connector elements are used for fixation.

The damping at one process connection in its order of magnitude corresponds to a non-reflecting boundary with respect to transverse vibrations. The boundary rigid body to couple in the damping from the process connection is shown in Figure 3.

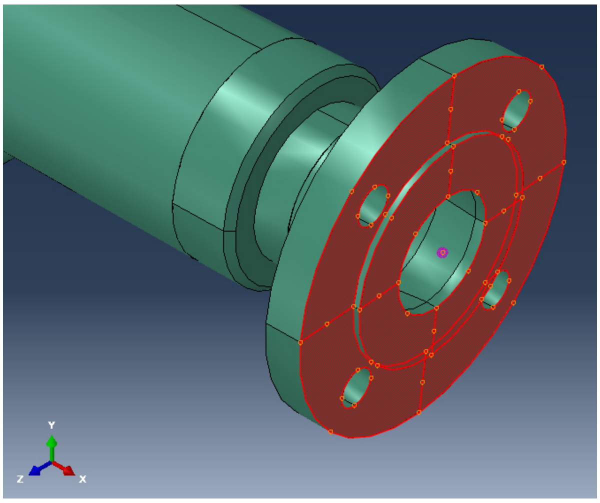

Figure 3. Rigid body definition for application of the localized boundary damper

3.   Results of the calculations

3.1   Accuracy of eigenfrequency calculation

The meter´s eigenfrequency is used for fluid density measurement. It is important to predict how this measurement value behaves under various internal or external parameter variations. As a model validation we compared calculations with a “good device” from research demonstrator production, and with a deliberately produced “bad device,” where tolerances had been intentionally relaxed.

A comparison of the eigenfrequency and its tuning behavior for the operation mode is given in Figure 4. It can be seen that deviations are usually well below 1%, and the tuning behavior is well predicted by the Abaqus model.

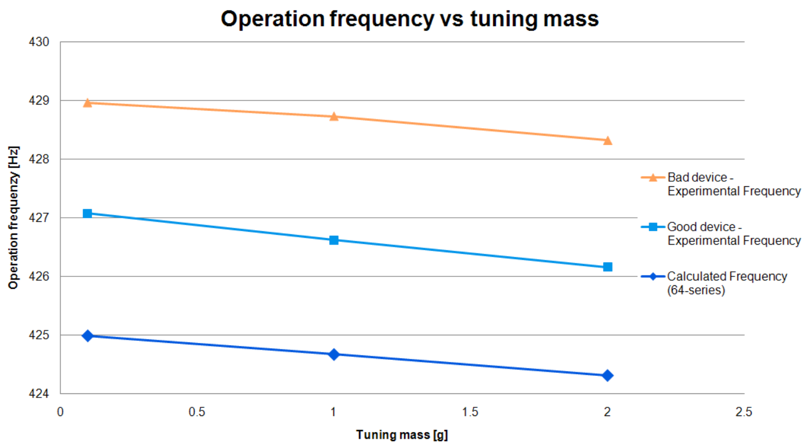

Figure 4. Comparison of the operation mode´s eigenfrequency calculation with experiment.

3.2 Zero phases

To avoid or minimize zero phases is among the main challenges in Coriolis meter design. Besides a fluid flow, other influences may cause phase shifts in the meter´s oscillation, irreproducibly interfere with the mass flow signal, and generate phases even when there is no mass flow. One mechanism for this zero phase generation is the presence of boundary dampers which break the $\pm x$ – Symmetry. The application of such a damper has been investigated for this report, since it is an important performance criterion for the design that its internal oscillatory phases are influenced as little as possible in such a load case.

3.2.1 Phase definition

Zero phases basically have to be extracted from the complex eigenmodes or from the complex response to a driving force via the formula

$$\Delta\varphi_0 = \arctan\left[\frac{\mathrm{Im}(v_{magnet}) - \mathrm{Im}(v_{coil})}{\mathrm{Re}(v_{magnet}) - \mathrm{Re}(v_{coil})}\right]_{plus} - \arctan\left[\frac{\mathrm{Im}(v_{magnet}) - \mathrm{Im}(v_{coil})}{\mathrm{Re}(v_{magnet}) - \mathrm{Re}(v_{coil})}\right]_{minus}$$

The motion of the system is purely harmonic in the steady-state situations which are considered here. So, the deformation $u(t) = u_0 e^{-i\omega t}$ at any given point is shifted by 90° in the complex plane against the velocity $v(t) = v_0 e^{-i\omega t}$. Therefore, instead of the velocity phase shift, one may equivalently use the phase shift of the deformations. The phase extraction formula and more involved post processing can be straightforwardly implemented in a python script for extracting phase values from Abaqus results data bases, for both `*Complex frequency` and `*Steady state dynamics, subspace projection`, jobs.

3.2.2 Phase field on the measurement tubes

For robust devices, zero phases for moderate disturbances are expected to be well below 1 m°, which is a very small quantity. In order to detect it numerically and reliably in calculations, it is often necessary to artificially strengthen the meter imperfections and afterwards scale down the effect to realistic values.

Very interestingly, in the case of twin bent tube meters, it has been found that a boundary damper causes considerable variations of absolute phase on each of the measurement tubes, as is shown in Figure 5. Schematically, the situation is shown in Figure 6. In spite of the very inhomogeneous absolute-phase field, the relative phase of the tubes, which is the relevant measurement value for flow, is detected correctly.

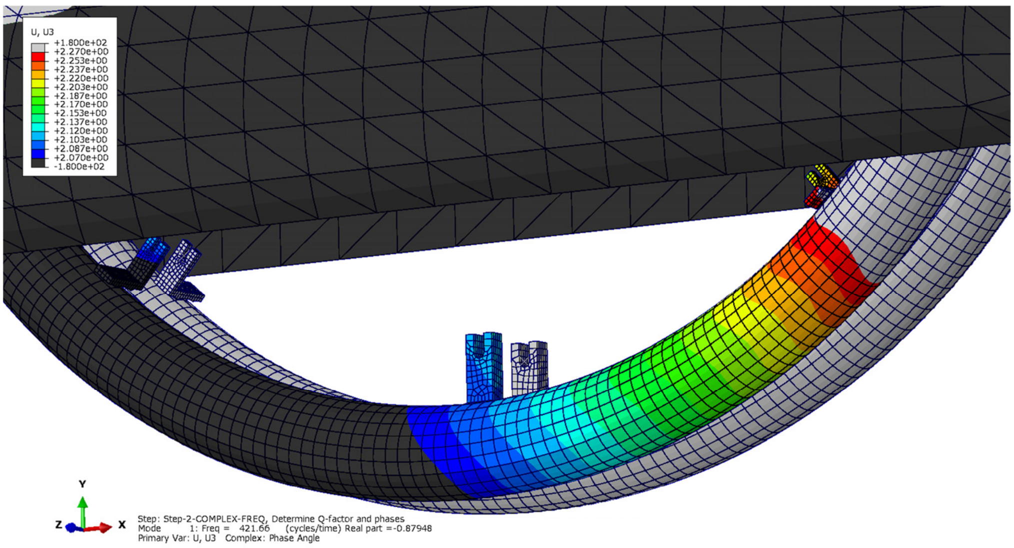

Figure 5. Phase distribution on one of the measurement tubes. The relative phase between one sensor magnet and the other (on the same tube) is approximately 100 m°. The zero phase, however, is only ~ -1.75 m°.

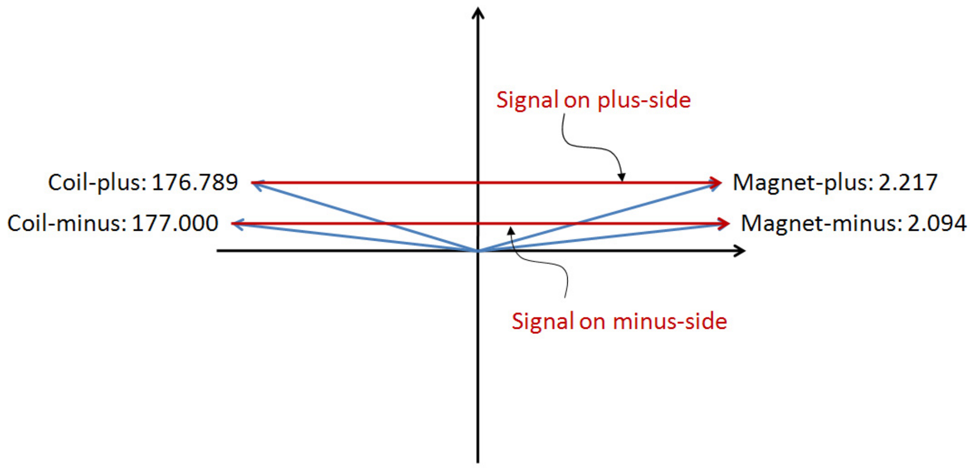

Figure 6. Schematic visualization of absolute phases of the magnets and coils for the case of 10g tuning mass in a phasor diagram. The relative phase of the signals is much smaller than the relative phase of, e.g., magnet motion. Note that the phases are given in degrees.

3.3 Comparison with experimental data for model validation

Again, the calculation results have been compared to a "good" as well as to a deliberately manufactured "bad" device. Results are given in Figure 7. In this study, of course, it cannot be expected to produce anything like coinciding curves. Too many details regarding the damping structure of real devices are unknown. Even the boundary damping which has been applied has not been specifically tuned to correspond to the experiment.

For the theoretically symmetrized system at approx. 0.1 g tuning mass, the model shows a very small zero phase. In experiment, both lab demonstrators show a non-negligible zero phase, a small one for the good device, a quite large one for the bad device. The latter phase even shows a different behavior in sign, when the tuning mass is increased.

To see that there is nevertheless a very good correspondence between good device and calculation, one re-calibrates the meter and checks for the variation of zero phase with tuning mass. It turns out that although the model contains only a very rough damping structure, it correctly predicts the order of magnitude of zero phase variation. This is an important point for evaluation of robustness of the measurement signal under internal and external parameter changes.

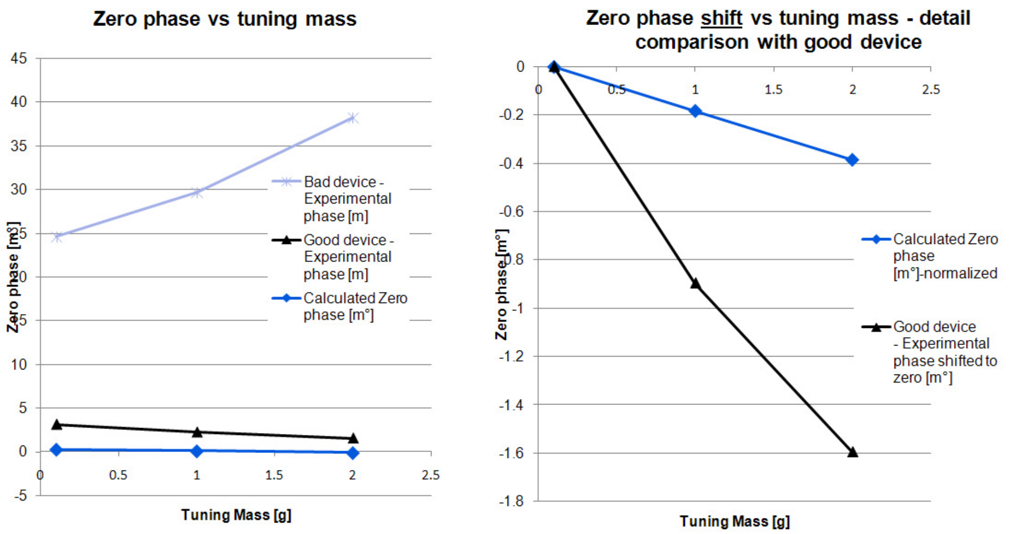

Figure 7. Zero phase calculation vs. measurements on a good and a bad device. The phase shifts with tuning mass agree with the good device up to a factor 4, which is satisfactory. Disagreements with the measurements on the bad device are considerably larger. The two devices even show a different sign of the zero phase shift.

3.4 Quality factors

A useful feature of the `*Complex Frequency` – procedure is that it immediately returns modal damping ratios. In our context of high-quality oscillations, we often work at the limits of resolvable modal damping. The smallest effective damping ratio which can be returned by Abaqus is $\xi = 10^{-5}$, corresponding to quality factor of $Q = 1/\xi = 10^5$. In practice, it turns out that in case of quality factors of more than 5000 the damping ratio is returned as zero.

The quality factors found in the model are measurable only for tuning masses larger than approx. 5 g. In this case, Q scales with the tuning mass with an exponent of approximately -2.3. A comparison of the calculated quality factors with experiment is shown in Figure 8. It has been expected that interaction with the damper increases with tuning mass due to the induced $\pm z$ – asymmetry of the mode form.

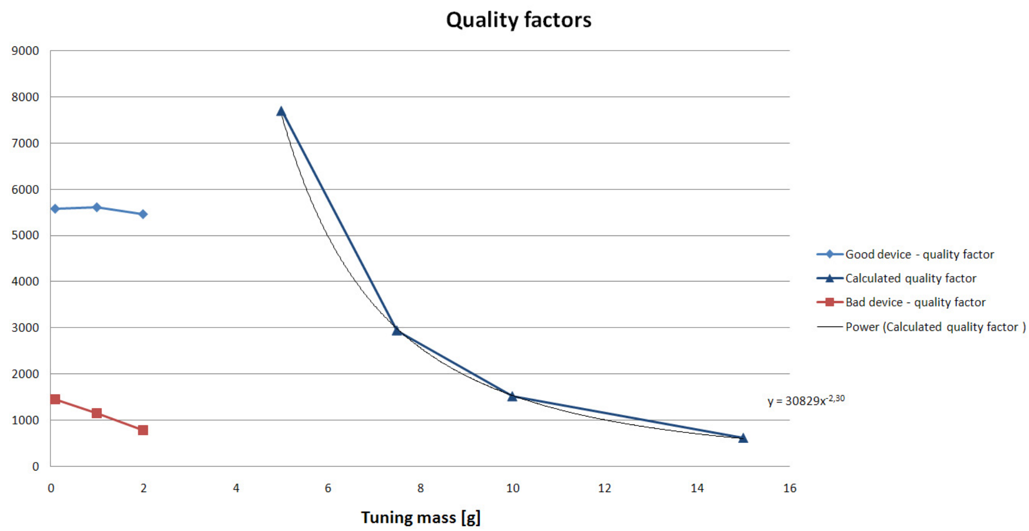

Figure 8. Calculated quality factors for a boundary damper, compared to experimental results. Since quality factors as such do not influence meter performance, no attempt has been made to fit the data by Rayleigh parameters.

The model shows that a strong external damper, together with internal asymmetries, can produce damping ratios in the same order of magnitude as they are measured. However, in experiment, damping is also present without deliberately applied asymmetry, and it varies quite strongly for different device specimens. So, in experiment, there seems to be some internal damping (rather strong in the case of the bad device) or some asymmetry from design tolerances. It is possible to reproduce experimental damping values by application e.g. of Rayleigh damping and local internal dampers, but that is not the subject of this study. The dependence of the quality factor on the material damping is shown in Figure 9, for the cases with and without external standard damper. It can be seen that the estimated value of Q ~ 38000 fits very well to the calculated values for larger damping. We also see that the localized damper at the flange gives quality factors of Q ~1500 for a 10 g tuning mass. The localized damper dominates the damping situation for $\beta \geq 10^{-7}$, approximately.

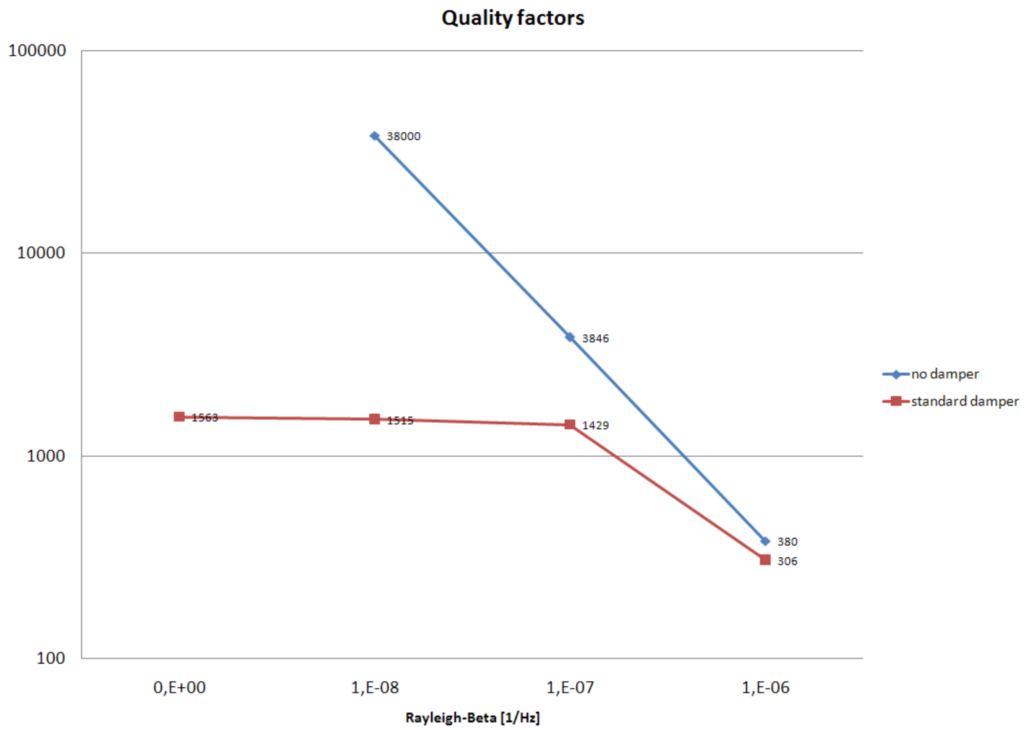

Figure 9. Quality factors with and without external damper. In all the cases shown here, the tuning mass has been chosen to be 10 g. All but one quality factor have been calculated in Abaqus. The value of 38000 in case of no external damper at β = 1.e-8 is the analytical estimate, which has not been resolved by the FE-calculation. Of course, *Q* diverges for the blue curve when β approaches zero.

4. Experiences

The following experiences could be extracted from the FE-studies of ABB CoriolisMaster demonstrators.

- For the boundary damper as used in this report, Rayleigh damping does not influence the phase generation. This is surprising, but even a β-value of 10^{-6}, which decreases the modal quality factor from approximately 1500 to 300, changes the phase only in the range of micro-degrees. The device remains stable.
- As a technical remark: Details of the damper´s coupling to the flange do not seem to play a major role. At least, reasonable variations of the rigid body area give only phase changes in the order of micro-degrees.

- Symmetrization of the system has a remarkable effect on the zero phase and the tuning behavior. It is shown in Figure 10. Obviously, and not too surprising, the order of the effect changes when starting from a fully symmetric situation.

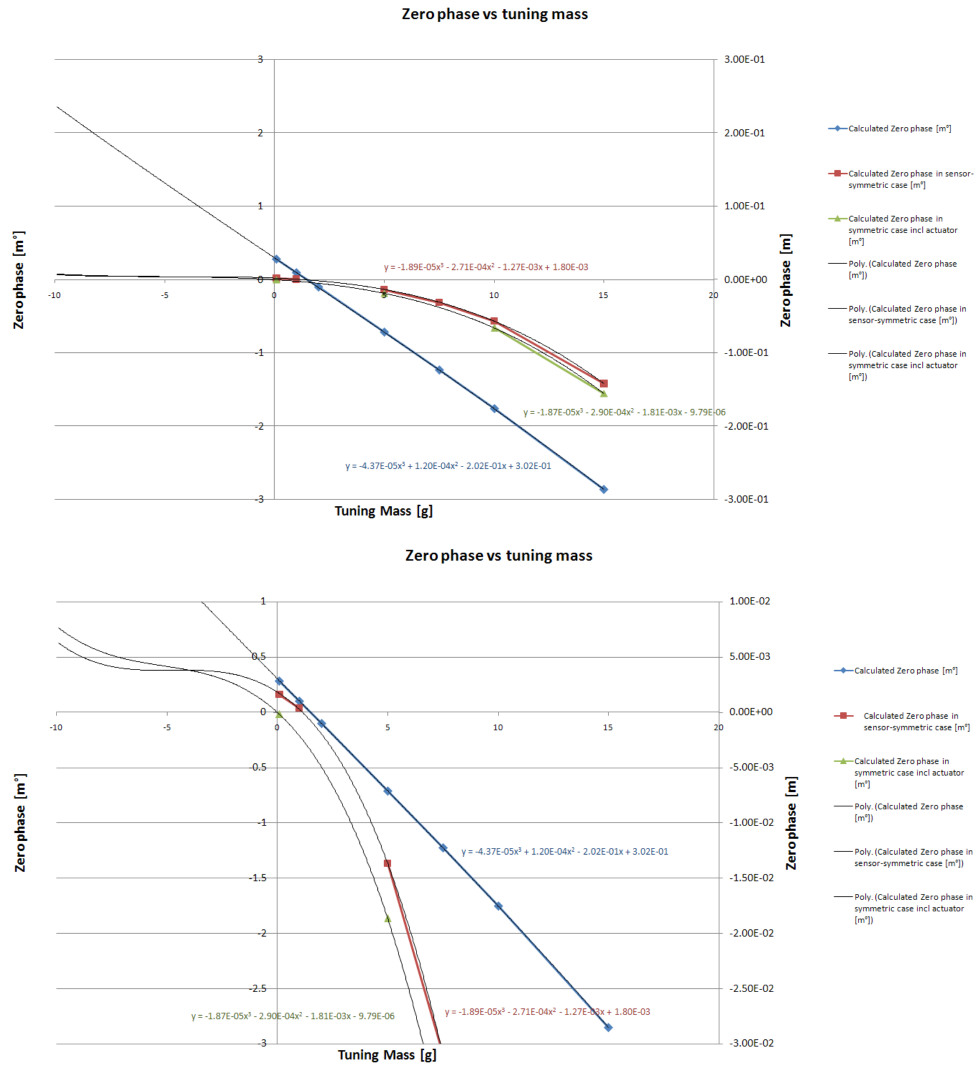

Figure 10. Zero phase vs. tuning mass for the default system (blue) and in case of successive symmetrization of sensors (red) and of actuator (green). For the latter two curves, the right *y*-axis applies, which is scaled up by a factor 10. The lower plot is just a zoom into the region around zero. The non-linear behavior after symmetrization can be well fitted by cubic or higher parabolae.

5. Conclusions

The Abaqus model at hand can be efficiently used to check the zero phase behavior and therefore the quality of Coriolis meter designs. It has been validated by experimental data with respect to vibration spectra, quality factors and zero phase order of magnitude.

The Abaqus calculation correctly detects very small zero phases even in situations with large absolute phases in the system or when damping ratios cannot be resolved any more.

Therefore, it makes sense to use the model for comparative studies in order to find out critical device parameters which influence the performance strongly. This includes:

- manufacturing tolerance analyses (Krafzick, 2012), which helped in finding reasonable tolerance specifications
- design purposes, e.g. for finding out an optimal housing without spoiling zero stability
- further risk management activities and performance criteria checks (thermal robustness etc.)

The formulation of specific device performance criteria in the form of Abaqus procedures with defined required results helped to make the product development of the ABB CoriolisMaster FCB330/350 successful and efficient. Follow-up investigations on reasonable tolerance specifications helped to optimize the cost structure and, therefore, to increase the customer value of the product.

6. References

1. Baker, R., "Flow Measurement Handbook," Cambridge University Press, 2000.
2. Abaqus User's Manual, Version 6.12-1, Dassault Systèmes Simulia Corp., Providence, RI.
3. Krafzick, Alexander, "Parametervariation Coriolismeter," SIMULIA Service, Internal Report for ABB, Jan. 2012.