Thermo-Mechanical Simulation of Die-Level Packaged 3-axis MEMS Gyroscope Performance

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Presented at the Inertial Sensors and Systems 2017 conference
Karlsruhe, Germany

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Abstract

In this paper we present accurate thermo-mechanical simulations of a MEMS gyroscope sensor, with its die-level package. The models, simulation tools, methodology and results are presented. The resonance frequency shifts of the modes of interest (drive and 3 sense modes) and the shift in sense capacitances are simulated and compared to experimental results. Simulations compare well with the results.

1. Introduction

MEMS sensors are generally designed to operate effectively over a specified temperature range. In consumer applications, for example, the operating temperature range typically extends from -40 to 85°C. In packaged MEMS, the interaction of the package with the transducer can lead to performance degradation due to temperature variation. For example, mismatching thermal expansion coefficients of the package and sensor materials leads to package deformation. This results in resonance frequency shifts and offsets in capacitive sensing gaps, all of which affect transducer performance.

The sensor considered in this study is a 3-axis capacitive Coriolis vibrating gyroscope developed by Murata Oy, see *Figure 1*. This device and its die-level package are studied with the Coventor MEMS design platform Coventor*MP*™. This platform combines two tools: CoventorWare®, for standard Finite Element Analysis (FEA) and *MEMS+*®, for efficient MEMS multi-physics simulations, see *Figure 2*. [Reference 1].

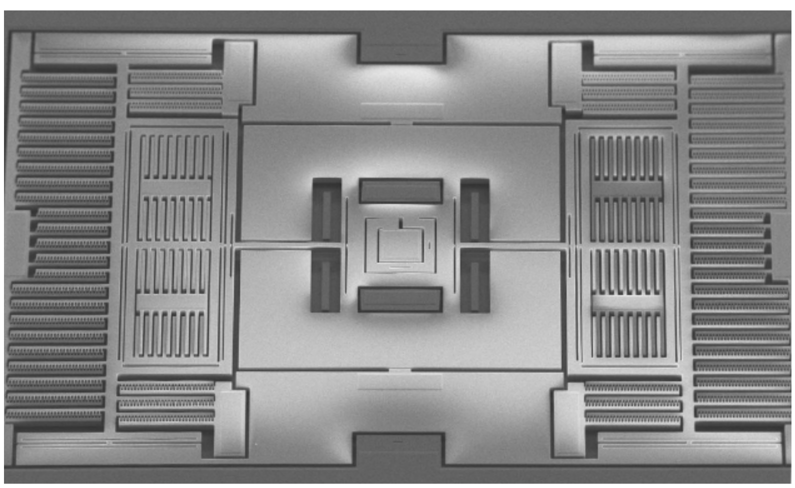

Figure 1. SEM image of the 3-axis gyroscope from Murata (without package top lid)

DOI: 10.1109/InertialSensors.2017.8171502

In general MEMS packages have dimensions an order of magnitude, or more, larger than the structures from which the transducer they contain is formed. Packages are also geometrically considerably simpler. Whilst a package is generally cubic in shape, a modern inertial sensor can contain many hundreds of connected shapes, for example sets of comb capacitors, suspension beams and inertial masses. The combination means modeling a MEMS transducer and its package using standard Finite Element Analysis can be challenging. This is particularly true when considering coupled-physics, where an extremely high number of standard finite elements can be needed to resolve both the geometry *and* accurately capture multi-physics behavior. One solution to this problem is to employ a hybrid approach, as available in Coventor*MP*. Here, the package is simulated using standard FEA and coupled to a model of the transducer created from specialized multi-physics finite elements, dedicated to MEMS transducer design.

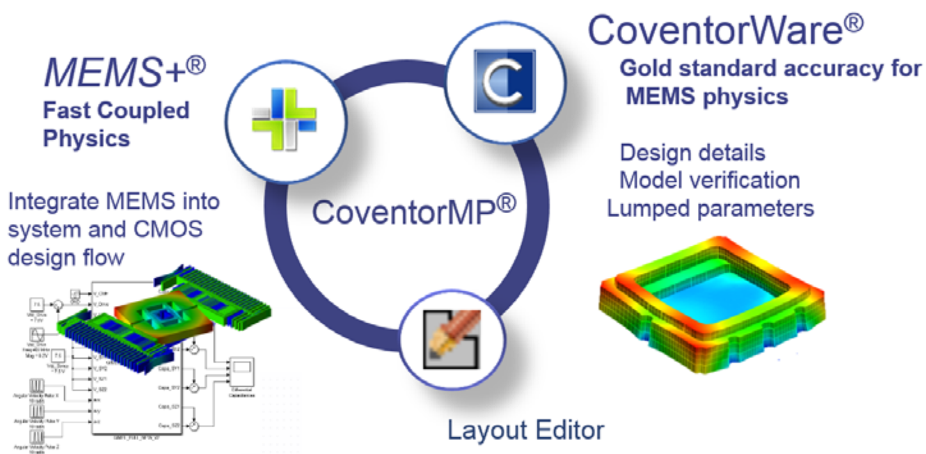

Figure 2. Coventor*MP* is a unified platform for MEMS design automation that c~~s~~ombines *MEMS*+ and CoventorWare

The design flow employed for this hybrid approach is illustrated in *Figure 3*. The thermo-mechanical behavior of the package is simulated using standard FEA and exported to a data file (A). The data file contains the package geometry and its thermo-mechanical behavior. A separate multi-physics model of the transducer is implemented in *MEMS*+ (B), and attached to the package, which is automatically imported from the data file. This complete model (transducer and package) can then be simulated within *MEMS+* or using MATLAB/Simulink® and Cadence/Spectre® (C).

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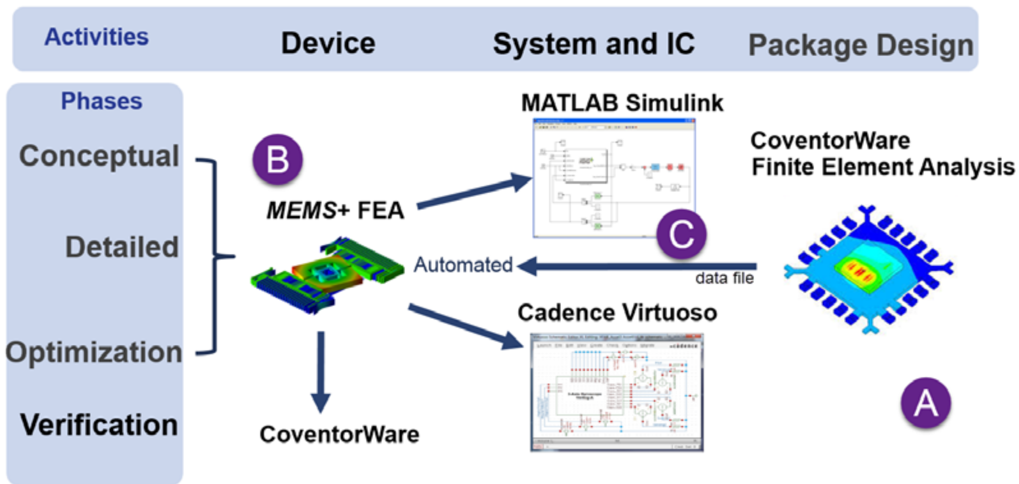

Figure 3. Coventor*MP* MEMS design automation flow

2. Description of the Modelling Approach for Package Deformation

This section describes the FEA package simulation, the *MEMS*+ model generation, and the transducer and package assembly.

2.1 Package FEA Model

Standard FEA is employed to simulate the die-level package deformation with temperature. The package is made of (100) crystal silicon and glass, of length 4 mm, width 3 mm and thickness 0.5 mm. The package model is meshed with 110 000 hexahedral 27-node brick elements, see *Figure 4A*) . The thermo-mechanical behavior of the package is determined with a temperature sweep analysis from -40°C to 80°C in 5°C steps. Specific boundary conditions are applied to allow a free to deform condition to model the soft glue that is used to fix the die-level package in place. *Figure 4B*) shows how the package warps at the edges due to temperature dependent material properties and thermal coefficient expansion mismatch between glass (3.25×10^{-6}°C^{-1}) and crystal silicon (2.6×10^{-6}°C^{-1}), where zero stress temperature is 20°C.

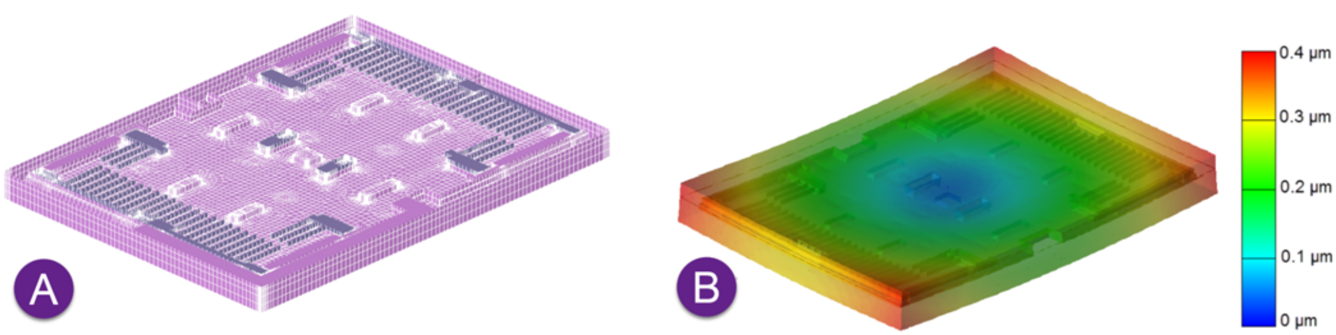

Figure 4. (A) Mesh of the package top lid of the gyroscope and (B).FEA simulation deformation results of the gyroscope die-level package at -40°C

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2.2 MEMS+ Multi-Physics Model

The gyroscope (without package) is modelled using *MEMS+*. *MEMS+* is based on a rich library of MEMS-specific parametric components, which are assembled into the desired structure [Reference 2], see *Figure 5*. Each *MEMS+* component has a 3D view associated with one or more underlying multi-physics finite elements (coupled mechanics, electrostatics and/or fluidics). The resulting model of the MEMS device has relatively few elements compared to a standard FEA model.

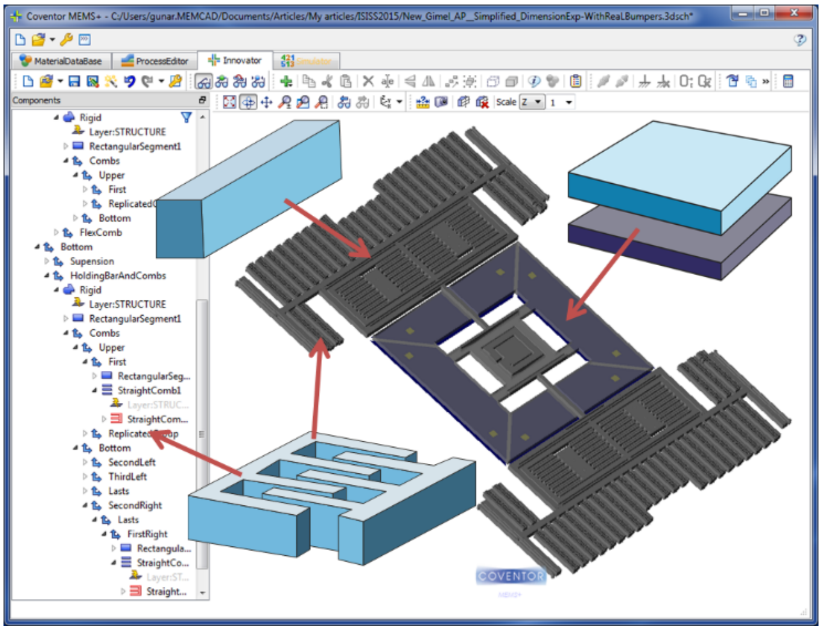

Figure 5. Gyroscope assembled with MEMS+ library components including straight beams, flexible plates, combs and electrodes

This approach yields a nonlinear, multi-physics, multi-domain model consisting of interconnected components: shell plates, Bernoulli beams, Timoshenko beams, electrostatic drive and capacitive sensing electrodes. *MEMS+* automatically assembles the individual component models into a single multi-physics system of equations [Reference 3]:

$$F\left(X, \dot{X}, U\right) = 0 \quad (1)$$

where $X \in \mathbb{R}^n$ is the state vector containing all the mechanical and electrical degrees of freedom (DoF). The input vector $U \in \mathbb{R}^m$ includes all input voltages, external accelerations and angular velocities $F: \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^n$ represents the sum of forces.

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The *MEMS+* model of the gyroscope in this study is internally represented by fully coupled nonlinear system matrices with 14,000 mechanical DoF, 10 electrical DoF, 3 angular velocity inputs and 9 capacitance outputs. Simulations show that the first five modal frequencies of the mechanical structure agree within 2% to of that predicted by a standard FEA. In addition, the model accurately captures electrostatic frequency softening and pull-in/lift-off, having been validated against experimental data [Reference 4-5].

2.3 MEMS+ Compact Model Including Package

The package deformation data is applied to the *MEMS+* model using a specialized package component, which loads the data file and images the 3D geometry. This component ensures that each *MEMS+* object in contact with the package is deformed or displaced according to the local, FEA-computed, nodal displacement of the package. This process is automatic, provided mechanical connectors have an initial position that touches the un-deformed package geometry, i.e. the package and transducer are positioned correctly. In multi-physics models, such as used in this example, geometry changes will also affect the position of electrical integration points and fluidic pins whose position depends on the mechanical connectors.

When sweeping temperature, package data files contain multiple data-sets, one set for each FEA temperature value. The specialized package component has a data-set field, which is normally user-configured so that the FEA data- set temperature value matches the MEMS+ simulation temperature. This ensures that as the simulation temperature in MEMS+ changes, the corresponding FEA package data- set is referenced, with values between sets being interpolated. As with the FEA package data, the MEMS+ material properties themselves are also defined to be dependent on temperature.

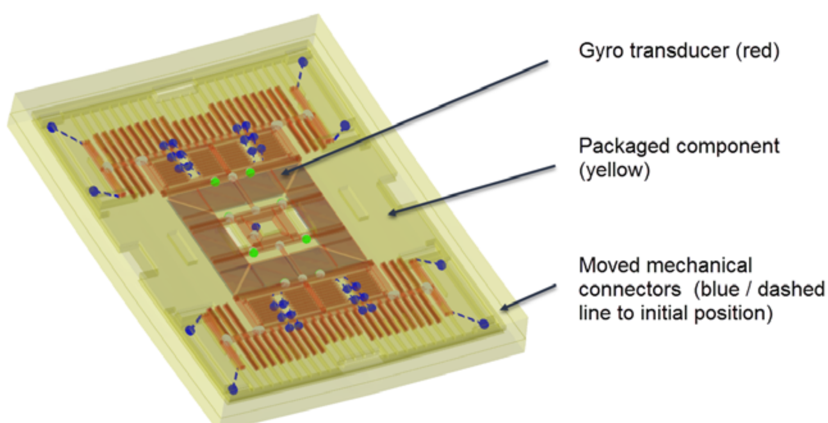

Figure 6. ***MEMS+*** **gyroscope and package model joined with mechanic connectors**

Figure 6 illustrates the transducer connection to the package. The blue colored small spheres are the mechanical connectors that join the transducer to the package. These connectors are shown in their *displaced* position, here exaggerated for clarity. A dashed line has been drawn in between the displaced connector and its (initial) un-deformed position. Once connected, a co-simulation of the package-transducer with temperature can be performed. For example, suspension anchor points may displace with

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temperature. Similarly, a sensing capacitor formed between a die-level package electrode and inertial mass may warp, leading to a change capacitance and gap damping values. Comb stators may also move, leading to changes in electrostatic drive forces and sensing capacitances.

3. Simulation and Experimental Results

In this section the performance and package of the gyroscope is evaluated by investigating the dependence of static capacitance, resonant frequency shifts and sensitivity with temperature.

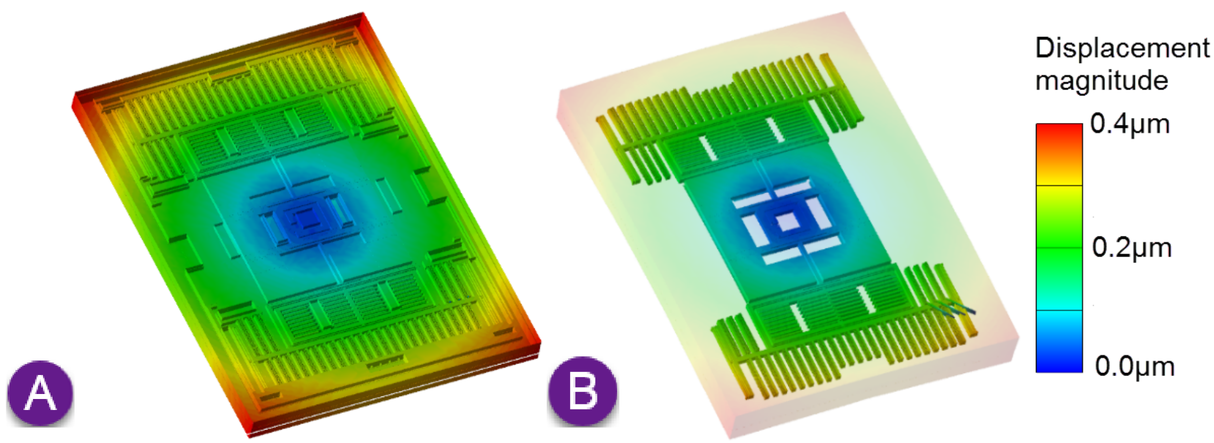

Figure 7. View of the thermal deformation results of the 3-axis gyro and die level package at -40°C. (A) top cap removed and (B) transparent package. – maximum deformation: 0.42µm.

3.1 Sense Capacitance versus Temperature

Figure 7 shows a 3D contour plot of the deformation of the Murata 3-axis gyroscope integrated into its die-level package. *Figure 8* shows a comparison over temperature of the measured and simulated capacitance for the x-axis sense mode. The simulation time is less than 1 second per temperature point (using pre-simulated package data). Simulation results and measurement are in good agreement. Note, the simulation results show a step change between 0^{o}C and 40^{o}C situated approximately at 20^{o}C, which corresponds to the zero-stress temperature. This effect might be due to the relative contributions from package-induced shift and that due to the pure material property changing with temperature. More investigation is required to clarify this point.

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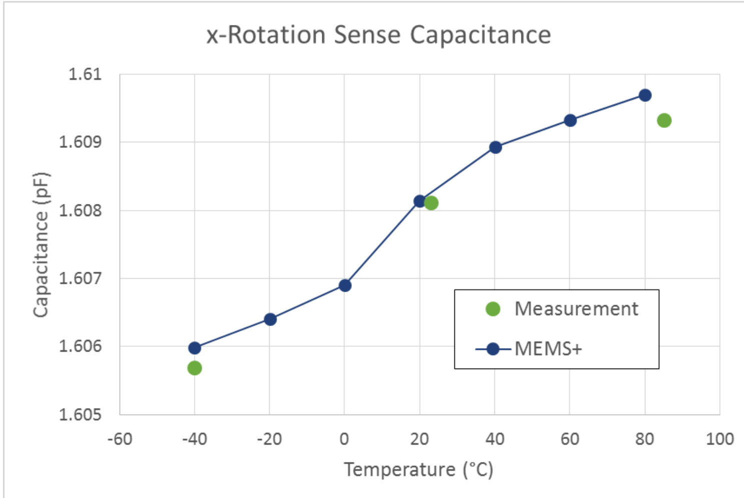

Figure 8. Capacitance versus temperature for the left x-rotation sense electrode

3.2 Resonance Mode Frequencies versus Temperature

There are 4 main resonance frequencies of interest in a 3-axis Coriolis vibrating gyro, the drive frequency and the 3 sense frequencies (one per axis) that amplify the Coriolis induced sense movements. The performance of the gyroscope is highly sensitive to these resonance frequencies. For example, gyro sensitivity is a function the sense and drive frequencies [Reference 6] and so understanding the frequency shift with temperature and the influence of the package is important. *Figure 9* compares simulated and experimental values for the gyroscope x-rotation sense resonant frequency and drive frequency with temperature. There is a good match between the simulated and experimental results. The measured data shows a small non-linearity, which is thought to be due to a second-order dependence of Young's modulus on temperature, not included in the simulation model.

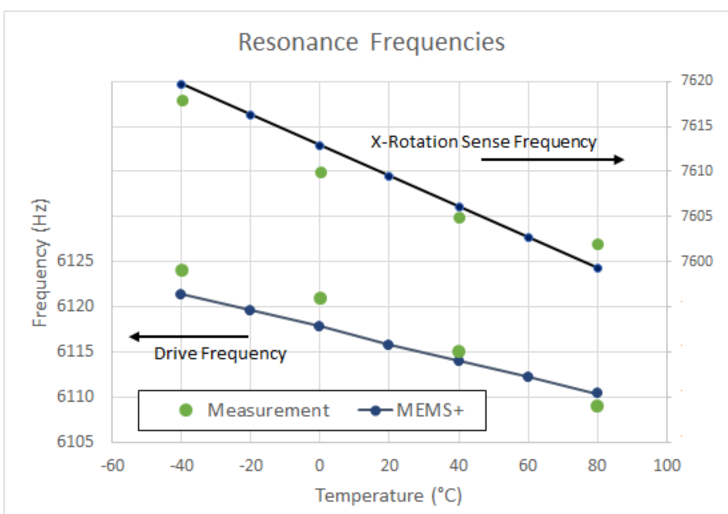

Figure 9. Drive and x-rotation sense resonance frequencies versus temperature

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3.3 Gyro Sensitivity versus Temperature

The predicated sensitivity of the gyroscope with temperature is shown in *Figure 10.* For this analysis, the gyroscope drive and sense electrodes are biased and a static angular rate of 1 rad/s is applied as an input to the inertial reference frame in *MEMS+*. A harmonic analysis with an AC magnitude applied to the drive combs is used to recover the amplitude of the x-axis sense signal, and so predict the sensitivity with temperature.

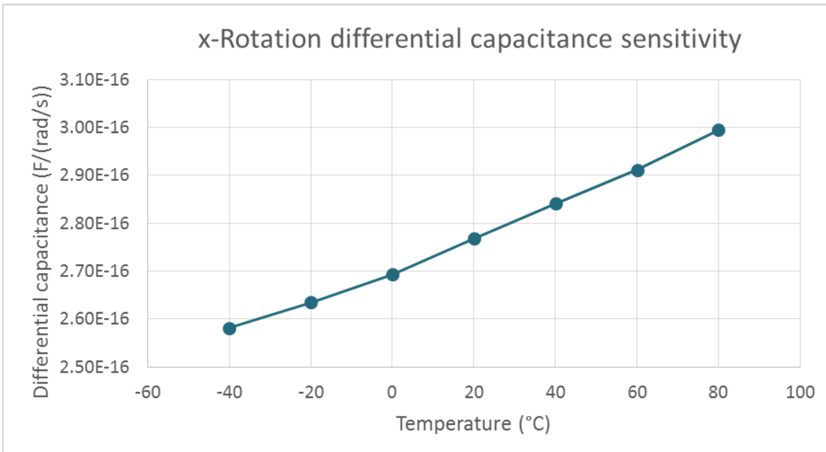

Figure 10. x-rotation differential capacitance sensitivity versus temperature

4. Conclusion

A hybrid solution to simulate a MEMS transducer integrated into its package has been presented. The hybrid solution enables the co-simulation of a multi-physics geometrically complex model with a simpler standard-FEA package model. The performance of a die-level package 3-axis gyro has been simulated with this hybrid solution. Thermo-mechanical simulations of the sense capacitances show good agreement with measurement. The simulations highlight a response not captured in the measured data, which warrants further investigation. Additional simulations have demonstrated the capability to predict frequency-shift and rate-sensitivity shift with temperature. The hybrid solution offers a practical and validated solution to simulate and improve the performance of packaged MEMS transducers.

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DOI: 10.1109/InertialSensors.2017.8171502