Dynamic fault injection for system level simulation of MEMS
– a design method for functional safety

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***Abstract* — In this paper a method for dynamic fault injection and fault simulation as well as its application to MEMS based sensor systems is described. The prerequisite for this approach is the availability of accurate, but numerically efficient models for the MEMS element. Simulations based on SystemC and SystemC AMS are suitable to analyze the nominal behavior of complex systems including electronics and the mechanical behavior of the MEMS elements [1], [2]. They offer capabilities to represent analog and digital hardware as well as software and nonelectrical components in one simulation environment. Especially for the modelling of mechanical structures, dedicated modelling algorithms like model order reduction [3], [4] have to be applied to ensure high numerical efficiency.**

Keywords — Behavioral modelling, modelling methodology, system level simulation, functional safety, robust design

I. Motivation

The increasing complexity of electronic systems, especially in the automotive industry, is characterized by the interaction of digital and analog hardware components including software, as well as non-electrical components such as sensor elements or actuators. Furthermore, demanding requirements concerning environmental conditions and variable operation scenarios lead to new challenges for design support.

Especially, risk analysis and verification of functional safety of such systems w.r.t. international standards becomes increasingly difficult and expensive. It is no longer sufficient to prove only the nominal function for all relevant operation modes. In addition, the impact of faults on the system behavior and its severity must also be investigated. Currently, a variety of techniques, e.g. failure modes, effects, and diagnostic analysis (FMEDA) or fault tree analysis (FTA) are applied. These approaches can be efficiently supported by modelling and simulation at electronic system level (ESL) [5]. To ensure not only the fulfilment of functional requirements, but also the functional safety of a system these design and verification tools must also include possibilities for analysis of faulty behavior. Such methods are strongly recommended or even required in standards for functional safety, e.g. in ISO 26262 for automotive systems.

In general compliance to functional safety requirements regarding the mechanical properties of MEMS prerequisites a comprehensive modelling of its mechanical behavior resulting from any kind of static and dynamic effects. In particular such properties as the stiffness and flexibility of the mechanical structure of the MEMS element, its frequency responses w.r.t. considered Eigen modes or the influence of different damping values will be investigated.

II. Fault injection as design method to ensure functional safety

Usually, previous approaches for fault injection implement faults by specific elements directly in the respective models. These faults are activated by certain events during the simulation. This mixed description of nominal and faulty behavior is an essential disadvantage because of possible inconsistencies [6]. The main advantage of the presented method is the explicit separation of the descriptions for the system, the test environment and injected faults (Figure 1). Faulty behavior is described instead at test level as fault scenario. During the runtime the test process will call dynamically the fault scenario appropriate to the considered objective of the specified test case.

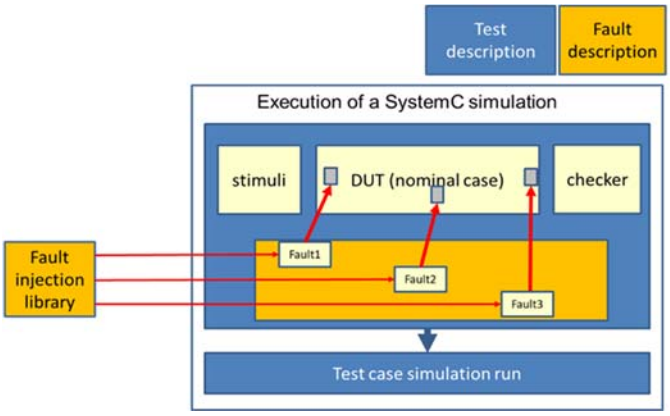

Fig. 1. schematic description of the fault injection during the simulation process [6]

A fault scenario consists of single or multiple faults which are represented by fault models. These basic fault models can be combined to describe a specific fault behavior and can be used universally for several system models and test cases. The extendable fault list and the injection method is implemented as a library for dynamic fault injection in SystemC and SystemC AMS descriptions which support various models of computation

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(MOC): Such as Transaction Level Modelling (TLM), Digital Event, Timed Data flow (TDF), electric Network (ELN), etc.[PS1]

This dynamic injection of additional fault-objects during the simulation run within test sequences of nominal behavior complies also to the standardized UVM-methodology.[PS2]

III. Verification Example of an MEMS-Accelerometer Adapted to Functional Safety Requirements

An application example of a closed loop controlled accelerometer is shown in Figure 2. It consists of a sensor model (MEMS structure) and electronic components implementing driving and sensing functionality.

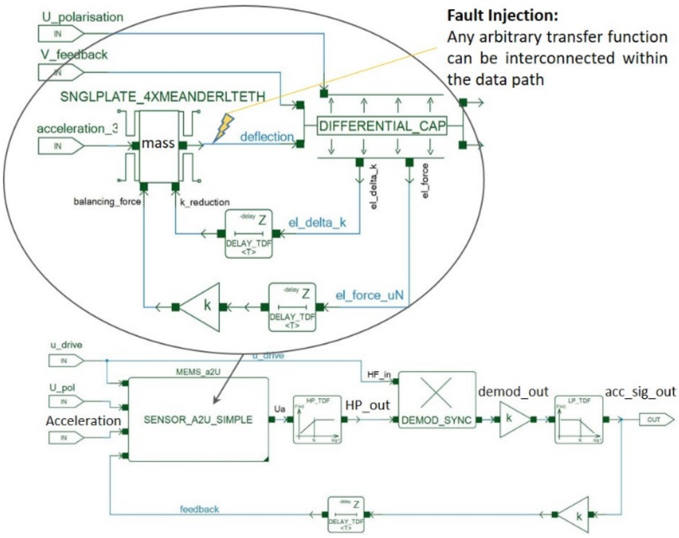

Fig. 2. ESL description of an accelerometer MEMS – in general at all ports of the internal modules additional fault injections are possible

Fig. 3 depicts a signal pattern of an acceleration profile between the top level components of Fig. 2. It is a result of a transient simulation for the nominal behavior of the system.

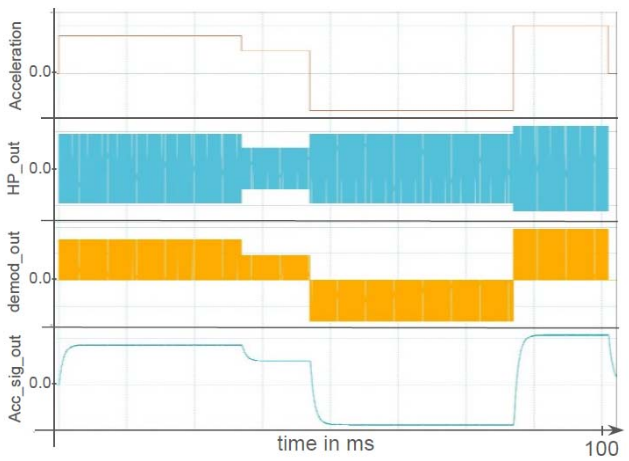

Fig. 3. Signals at the data path processing of an nominal acceleration profile – traced on the signals of top level in Fig. 2

The MEMS model focusses on the mechanical properties and its possible faults. The following mechanical faults of a MEMS element are considered:

- Increase of damping values due to a higher pressure level
- Interfering motions due to additional parasitic excitations of other Eigen modes
- Contaminations resulting in increased damping values or resulting in reduced mechanical flexibility to narrow possible deflections[PS3] of the MEMS element
- Fractures and resultant loss of the inertial mass or the spring stiffness due to an exposure to mechanical stress
- Pull-in state due to a too high deflection behind the limits [RJ4]of the electrostatic pull

Due to the modularized structure of this accelerometer, models with different levels of complexity can be used. The selected model depends on the considered properties, which should be analyzed and verified. Especially for the modelling of mechanical properties of the MEMS sensing element two different modelling methods are possible [7]:

- A mathematical description of physical properties (e.g. geometrical dimensions, stiffness, damping, mass etc.). For example composed cantilever beam models or membrane descriptions can be described in context [RJ5]of its specified physical meaning. Basic model arrangements can also be enhanced to a single mass-spring-system describing the dynamical behavior in the specified Eigen mode. This will be described by a single linear differential equation (1).
- A structural description in representation of a state space model. This description can be derived by a model order reduction [3] directly from the FE model of the designed MEMS-structure (Fig. 7) This reduced structural description shows within the selected frequency range an approximate behavior of the FE mesh model with considerable less computational effort.

The great advantage of the second mentioned approach is a representation of the whole dynamic behavior of any existing Eigen modes within a specified range [1]. Since the structural description originates from the design data of the developed MEMS element, the consistence between the model and the design is ensured. A disadvantage of this modelling method is the loss of the dedicated geometrical and physical meaning of each state element within the reduced system matrix. Hence, an direct influence of a specified physical property and therefore also any direct injection of a possible fail-behavior is not feasible. On the contrary the direct implementation of the dedicated physical properties (such as stiffness and damping) within the ESL model provides the possibility of a direct fault injection within the mechanical domain.

As shown on the flash sign in Fig. 2 a failure injection into the data path can be performed as an additional intermediate transfer function or as a statically acting coefficient. Complying to the rules of system theory an additionally injected failure function in the data path will be effectively a multiplication with the prior function. In contrast, an injected failure parallel to the nominal behavior would be effectively an addition to the prior function. See Fig. 4 below:

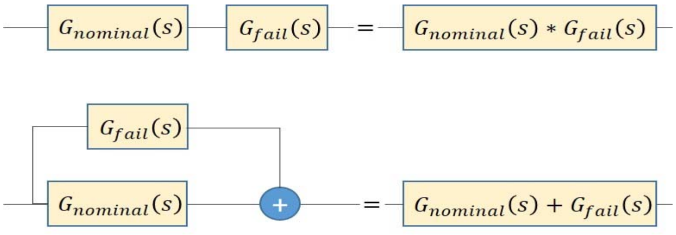

Fig. 4. composing rules of injected failure functions to the resulting transfer function

Depending on the required test scenario the fault injection must be performed by an adapted additional transfer function to realize in summary with the nominal transfer function the particular investigated faulty behavior. Considering the mechanical behavior of a MEMS the composing rules of Fig. 4 are utilized in an example of failure injection showing an increased damping effect within the MEMS element. This fault scenario of an increased damping can be realized with a transfer function injected in the data path, which is adapted to the physical relations of the mass spring system between the mass *m*, damping *D* and the cantilever spring stiffness *K* shown in (1 – 3)

$$-F = \ddot{x}m + \dot{x}D + xK \text{[PS6][TB7]} \quad (1)$$

differential equation of the dynamic mass spring description

$$G_{mass\ spring\ syst}(s) = \frac{1}{\frac{m}{K}s^2 + 2D\sqrt{\frac{m}{K}}s + 1} \quad (2)$$

Nominal Laplace transfer function in the frequency domain

$$G_{fail_{(band\ gap)}}(s) = \frac{s^2 + \frac{K}{m}\left(1 - \sqrt{D_{fail}}\right)}{s^2 + \sqrt{\frac{K}{m}}D_{fail}s + 2\frac{K}{m}\left(1 - \sqrt{D_{fail}}\right)} \quad (3)$$

Laplace transfer function of an injected band attenuation

Fig. 5 shows an increased damping behavior as a failure function. The intermediated failure injection shown in Fig. 6 does affect the resonant deflection within a switch on – switch off scenario during a harmonic excitation at a sweeping frequency.

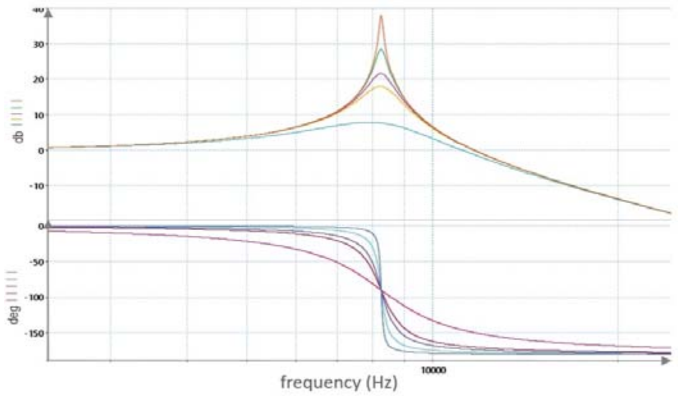

Fig. 5. Frequency response of a mass spring system with an injected band attenuation. In summary it will affect as an additional damping value.

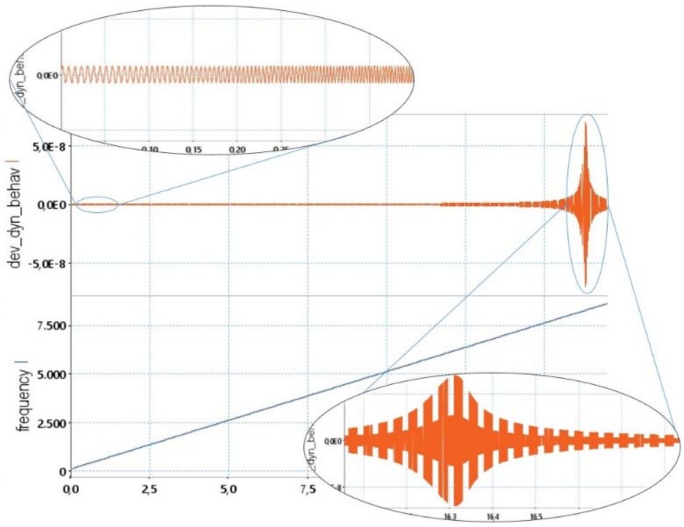

Fig. 6. time domain of the dynamic mass spring behavior with the repetitive switched band attenuation – exitated by a sweeping frequency

Enhanced structure models of the mechanical MEMS behavior derived from a FE model as shown in Fig. 7 provide dynamic descriptions of multiple Eigen modes at different kind of excitations. Due to their physical properties being transformed into abstract state elements an influence of a dedicated property is not possible. But the subsequent injection of an adapted transfer functions into their output elements is a suitable method to influence the dynamical behavior of these models.

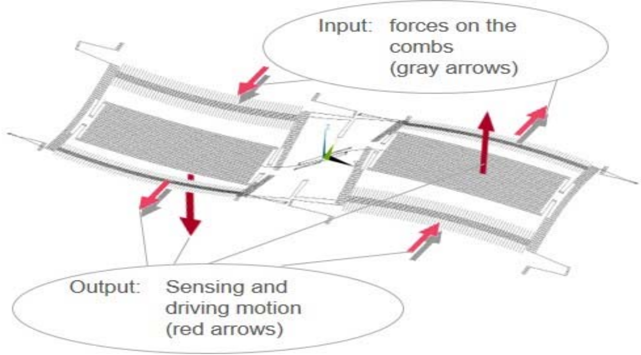

Fig. 7. FE mesh of a MEMS element with different types of exitation

The reduced state space description of the MEMS element can be implemented within a data path of an ESL description as shown in Fig. 8. Because the data path is almost a vector with multiple input and output elements for different positions and mechanical degrees of freedom (DoF), a much more detailed dynamic behavior can be simulated.

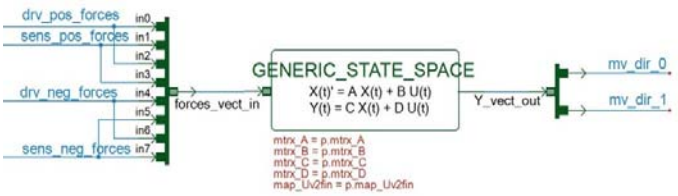

Fig. 8. Reduced state space description of the MEMS element connected into the data path of an ESL description

Also the dynamic behavior of every particular data path element will be represented much more detailed with additional higher Eigen modes. Fig. 9 shows the frequency response of the excitation in sensing direction at the MEMS element depicted within Fig. 7.

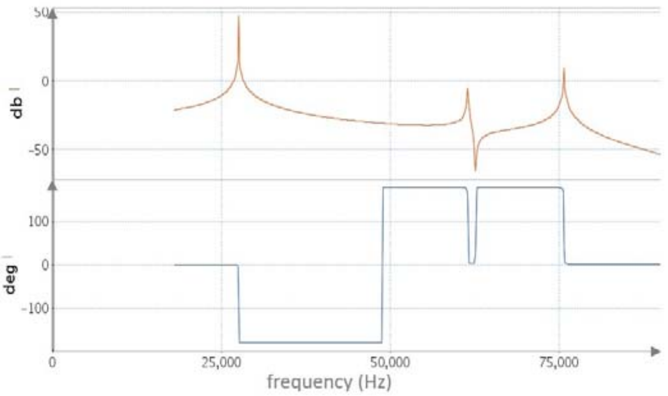

Fig. 9. Frequency response with higher resonant Eigen modes at a sensing motion

According to the rules of system theory the modelling approach with the use of additional injected transfer functions is limited to data path elements without feedback effects. The reason of this restriction is the frequency dependent phase shift of the output signal behind an additional injected transfer function. However, in the case of an existing feedback loop in the system nevertheless this approach could be used, if the feedback path will be delayed depending on the used frequency. Any static injections without phase shifting behavior remains unaffected of the above mentioned restrictions.

IV. Conclusions

In general the design methodology of additionally injected transfer functions together with the enhanced structure descriptions of MEMS elements is a powerful approach for the system level verification. As the fault injection can influence every element of the data path, the resulting impact of many mechanical failures or other external influences can be simulated in a very detailed and realistic approximation. The dynamic injection of faults or any additional influence complies to the required strict separation of design data from test case scenarios.

Relating to the verification requirements of the functional safety, structural models of MEMS provide an enhanced description of its system behavior. That means in particular the dynamic behavior description of multiple mechanical DoF on multiple relevant positions of the MEMS element. [PS8]Hence this comprehensive modelling method is suited to simulate also indirect acting failures or influences effective on their output data path vectors.

References[PS9]

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