Subproject A2: "A system level model in VHDL-AMS for a micromechanic vibration sensor array"

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ABSTRACT

A new capacitive vibration sensor using an array of laterally moving mass-spring systems is being developed at Chemnitz University of Technology [1]. The sensor operation is based on narrow-band resonance of the mass-spring elements. The natural frequency of each element can be tuned electrically. The sensor is intended for application in wear state recognition on highly stressed machine components.
The paper is focussing on high abstraction level CAD modeling of the sensor array. A new design approach [2], efficient choice of physical domains, resulting problems and their solutions will be shown in connection with the design of both sensor and analog signal processing models.

1 Introduction

The new sensor array which is being developed at Chemnitz University of Technology is fabricated by a SCREAM technology. Because of the narrow-band resonance working mode, the signal processing can be simplified due to a better signal to noise ratio and because no FFT is needed. So a low cost sensor system can be built.
The sensor system should be tested using the experimental prototype „vibration sensor array". But before the construction of the experimental prototype a simulation of the whole system is necessary to check the functionality of the individual components and their interaction. The function of the sensor was simulated by FEM simulation during the development of the sensor array. For simulation of the system including the sensor, analog and digital signal processing an FEM simulation takes too much time. Additionally, a simulation environment is necessary which allows simulation of mechanical, analog electrical and digital systems. So a model at a high abstraction level was developed using the VHDL-AMS hardware description language.

2 The system experimental prototype "vibration Sensor array"

The sensor system consists of a sensor array containing eight individual mass-spring resonators, with an electrically tunable natural frequency each, an analog signal processing unit and a high voltage amplifier. The system is controlled by a micro controller. The system also includes a fuzzy pattern classification system [3].

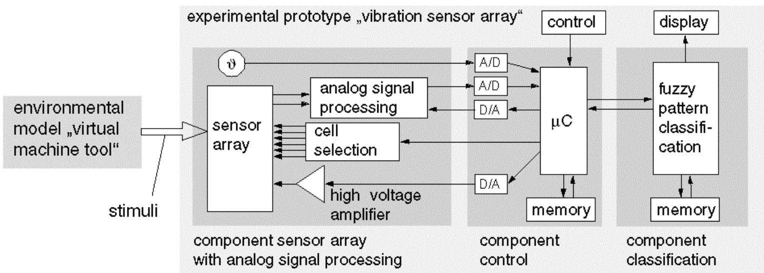

Fig 1: Block diagram of the experimental prototype „vibration sensor array"

An environmental model called „virtual machine tool" provides the stimuli for simulation. It reproduces measured data in time or frequency domain or generates fictitious data. The vibration sensor converts this mechanical stimulation frequency-selectively into an electrical signal. Analog signal processing amplifies this signal and extracts the magnitude at a specific frequency. The individual resonators in the sensor can be activated separately, in groups or all together by a cell activation unit. The high voltage amplifier generates voltages up to 30 V for the natural frequency tuning of the sensor. A micro controller starts or stops the measurement, activates or deactivates resonators and starts self-calibration. It tunes the natural frequency of the resonators and transmits measured data to the classification unit. The classifier decides by a fuzzy pattern classification algorithm whether the data are produced by an sharp or worn out tool. This algorithm is realized in a FPGA.

3 Models of the sensor

The sensor consists of an array of 8 laterally moving mass-spring resonators (spring, seismic masse and damper). They work in a frequency-selective resonant mode. To allow measurements at variable frequencies the spring constant and, therewith the natural frequency is tuned by an electrostatic force. The response of the structures is detected capacitively by comb electrodes at the seismic mass.
During its development the sensor was simulated and optimized by FEM simulation. But for system simulation, FEM simulation is too slow. So the sensor was modeled and simulated in the VHDL-AMS hardware description language. The advantage of using VHDL-AMS is that these components can be modeled in the mechanical domain directly without any analogy transformation. This means that the behavior of a spring can be described as $F = k \cdot s$ (force, spring constant, displacement). With a SPICE-like analogy transformation the modeling of the mechanical behavior is limited to electrical equivalents whereas in VHDL-AMS it is possible to describe every linear and nonlinear behavior between force and acceleration, velocity or displacement.

3.1 Tuning by stress-stiffening

The first variant of tuning the natural frequencies is using the stress-stiffening effect. Figure 2. shows a schematic of the sensor and its functional principle.

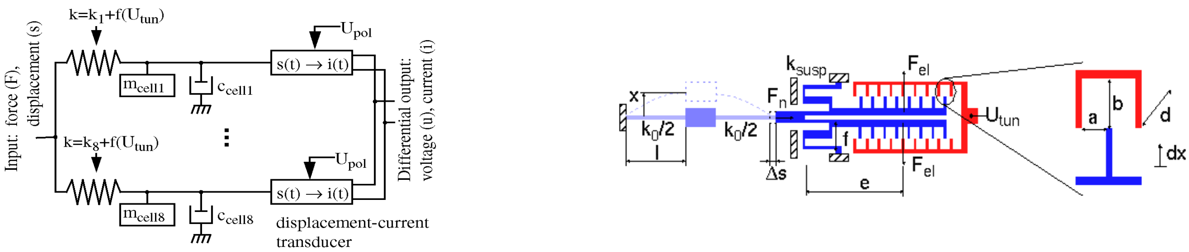

Fig 2: Schematic of the sensor array and extracted detail of a mass-spring resonator

The stress-stiffening unit is driven by an electrostatic force F_{el}. This force is caused by the voltage U_{tun} and can be calculated as follows:

$$F_{el} = \frac{dW}{dx}, \qquad dW = \frac{1}{2} \cdot U_{tun} \cdot dC \qquad \text{(eq. 1)}$$

The capacitance of the comb structure can be calculated by the simplification of a homogeneous field of a plate capacitor:

$$C = 2n \cdot \varepsilon \cdot \frac{x_{ss} \cdot d}{a}, \qquad \frac{dC}{dx} = 2n \cdot \varepsilon \cdot \frac{d}{a}, \qquad F_{el} = U_{tun}^{\,2} \cdot \frac{n \cdot \varepsilon \cdot d}{a} \qquad \text{(eq. 2)}$$

where n is the number of combs. The force F_{el} generates by a lever mechanism (e, f) a normal force F_n [1]. This force influences the spring constant by the stress-stiffening effect:

$$F_n = 2 \cdot \frac{e}{f} \cdot F_{el} + \frac{6 \cdot k_{susp}}{5 \cdot l} \cdot x^2, \qquad k = k_0 + \frac{12 \cdot F_n}{5 \cdot l} \qquad \text{(eq. 3)}$$

The following part of the source code shows the implementation of this stress-stiffening effected spring in VHDL-AMS.

```
ENTITY stress_stiffening_spring IS
  GENERIC( n,a,b,d,e,f,
           k0,ksusp,l,eps:real);
  PORT( TERMINAL t1,t2: mech_F_s;
        TERMINAL t_tun: electrical);
END;
```

```
ARCHITECTURE behav of stress_stiffening_spring IS
  QUANTITY x ACROSS f THROUGH t1 TO t2;
  QUANTITY u_tun ACROSS t_tun;
  QUANTITY fel,fn: real:=0.0;
  QUANTITY k: real:=k0;
BEGIN
  fel==u_tun**2 * eps*n*d/a;
  fn==2.0*2.0*e/f*fel + 6.0*ksusp/5.0/l*x**2
     --two stress-stiffening actuators per spring
  k==k0+12.0/5.0*fn/l;
  f==k*x;
END;
```

3.2 Tuning by an electrostatic spring

Tuning by stress-stiffening has two disadvantages. The fabrication of this structure is difficult because of strain in the layers. Additionally, the lever mechanism is causing non-linearities in the behavior (eq. 3). So an alternative approach was tested. In this approach the spring constant is kept constant. The tuning of the natural frequency is done by a curved comb structure where the attraction force is a linear function of the displacement. The curve was optimized by FEM simulation. For system simulation it can be assumed to be a linear function. Analogous to equation (eq. 1) the force in the electrical field of this comb structure can be calculated as follows:

$$F_{el} = \frac{1}{2} \cdot U_{tun}^{\ 2} \cdot \frac{dC}{dx} \qquad \text{(eq. 4)}$$

The capacitance of this comb structure can be calculated by the simplification of the homogeneous field of a capacitor within the range $-(b-c) \le x \le (b-c)$:

$$C = 2 \cdot \varepsilon \cdot \frac{d \cdot x}{a} \cdot \frac{x}{b-c} \cdot n \cdot \frac{1}{2}, \quad C = \varepsilon \cdot \frac{d \cdot x^2}{a} \cdot \frac{n}{b-c}, \quad \frac{dC}{dx} = 2 \cdot \varepsilon \cdot \frac{d \cdot x}{a} \cdot \frac{n}{b-c} \qquad \text{(eq.5)}$$

$$F_{el} = U_{tun}^{\ 2} \cdot \varepsilon \cdot \frac{d \cdot x}{a} \cdot \frac{n}{b-c} \qquad \text{(eq. 6)}$$

Because F_{el} and the force of an ordinary spring are acting in opposite directions, the following can be written:

$$F = k \cdot x, \quad k = -\left(U_{tun}^{\ 2} \cdot \varepsilon \cdot \frac{d}{a} \cdot \frac{n}{b-c}\right) \qquad \text{(eq. 7)}$$

Figure 3 shows the structure of the sensor array model with this kind of tuning the natural frequency.

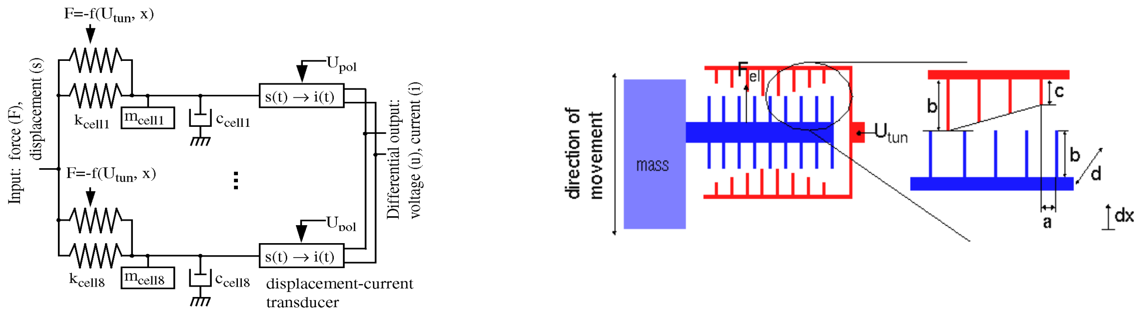

Fig 3: Schematic of the sensor with electrostatic softening and extracted detail of the electrostatic softening

4 Results

The models described above have been simulated by Mentor Graphics' AdvanceMS on a SUN ULTRA60 workstation with UltraSPARC-II 296 MHz CPU.
The first step in system simulation was the simulation of the sensor array. Figure 4. shows the spring constant as a function of the tuning voltage with tuning by stress-stiffening effect (red curve) and the spring constant of the electrostatic softening structure corresponding to equation 7 (green curve).

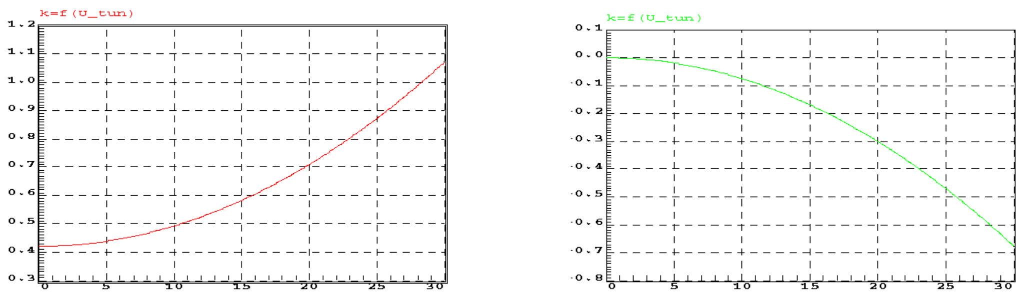

Fig 4: Spring constant with stress-stiffening effect as a function of tuning voltage

It can be seen easily that the spring constant with stress-stiffening influence increases with tuning voltage. In opposition to this the spring constant of the softening structure assumes a negative value. This means that this spring will produce an attraction force when it is being compressed. For tuning the natural frequency of the mass-spring element this electrostatic softening structure is mounted parallel to the normal spring of the system (see Figure 3.) and so the spring constant of this structure can be modified by tuning voltage.

The simulation of these sensor parts required only a few seconds computing time. The simulation inaccuracy of the softening structure is 4 % as compared with the FEM simulation. For the stress-stiffening structure the error as compared with the FEM simulation is about 10 %. An error of 10 % may seem to be too high but for system simulation this accuracy should be sufficient.
The next steps in the simulation process were the simulation of the whole sensor array and the simulation of analog signal processing. Finally, the system consisting of sensor array, stimuli generation and analog signal processing was simulated completely. A simulation result can be seen in Figure 5. The first curve displays the stimuli of the sensor provided by the „virtual machine tool“. Curves two through four show the response of the first three mass-spring systems of the sensor array. The tuning voltage is set to 12 V so cell 1 is tuned to a natural frequency of 1 kHz. The last two curves show the electrical response of the sensor after passing the differential amplifier and the response of the lock-in amplifier.

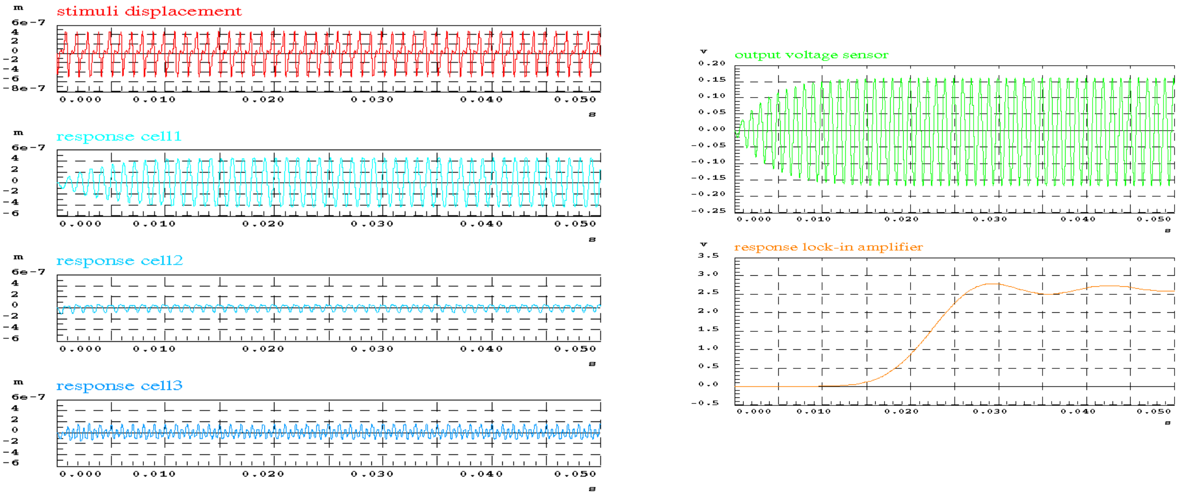

Fig 5: Stimuli and response of system simulation

The simulation time of this system is less than 5 minutes. In comparison to this, an FEM simulation takes about 20 minutes to simulate one comb structure only.

5 Conclusion and outlook

Simulation of the sensor array in combination with analog signal processing and the environmental model allows to show the function of the system before the realization of the hardware. Due to the short simulation time an interactive optimization of the system is possible, and also the interaction between the components can be tested easily.
At the moment the models for the whole experimental prototype „vibration sensor array“ are not yet complete. The digital component „control“ still has to be implemented. When this is done it will be possible to simulate whole measurement cycles in relative short times.

REFERENCES

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