A system level model in VHDL-AMS for a micromechanic vibration sensor array

Michael Schlegel, Göran Herrmann, Dietmar Müller
Faculty of Electrical Engineering and Information Technology,
Chemnitz University of Technology, Germany

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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. 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 poster is focussing on high abstraction level CAD modeling of the sensor array. A new design approach, 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.

The 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 and will also include a fuzzy pattern classification system.

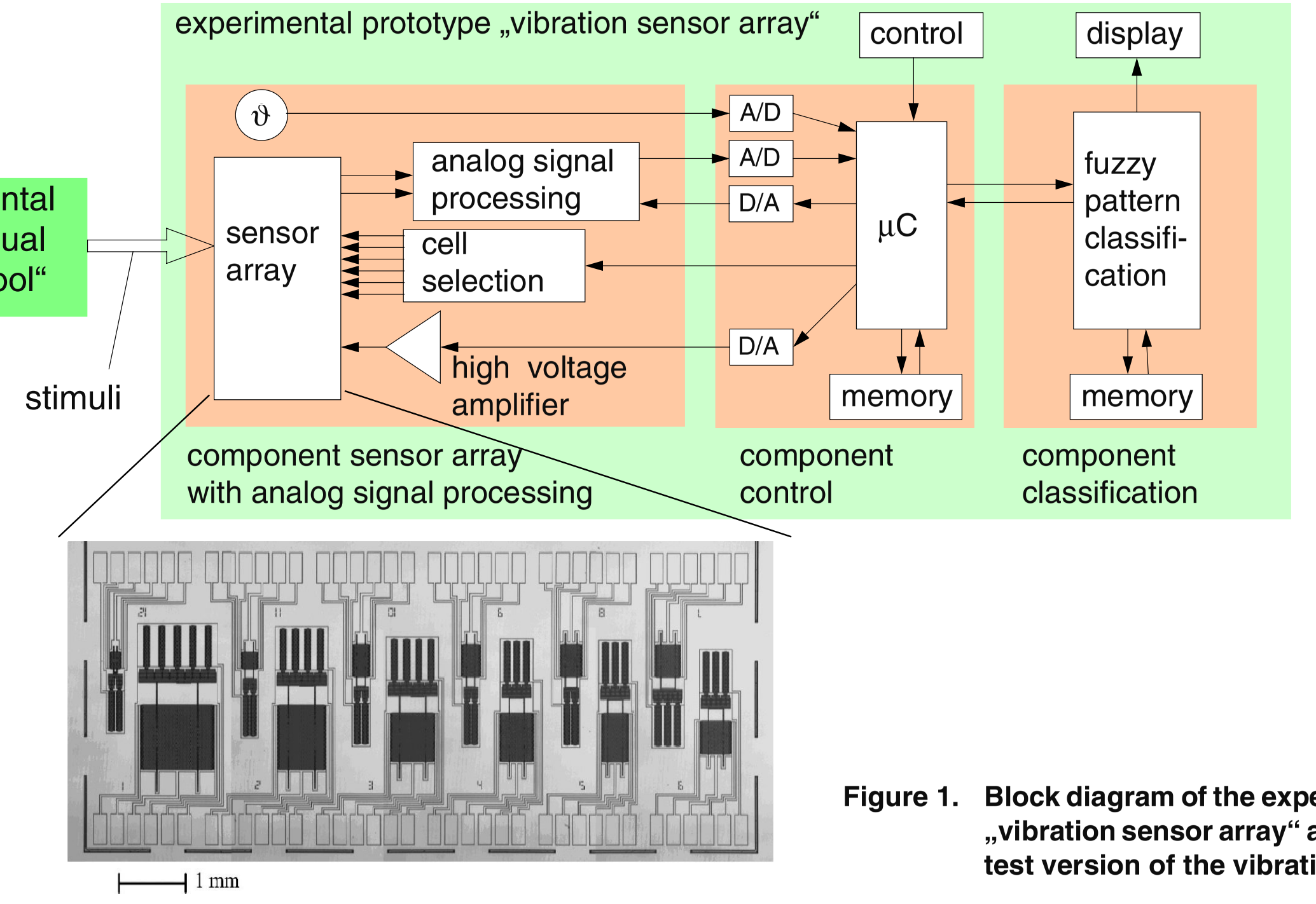


Figure 1. Block diagram of the experimental prototype „vibration sensor array“ and photograph of a test version of the vibration sensor

Frequency Tuning

The laterally moving mass-spring resonators of the sensor 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.

Tuning by stress-stiffening

- Stress-stiffening effect: increasing of the spring constant by a tensile stress applied to the flexure.

Figure 2. shows the functional principle of one mass-spring resonator and the natural frequency tuning by the stress-stiffening effect.

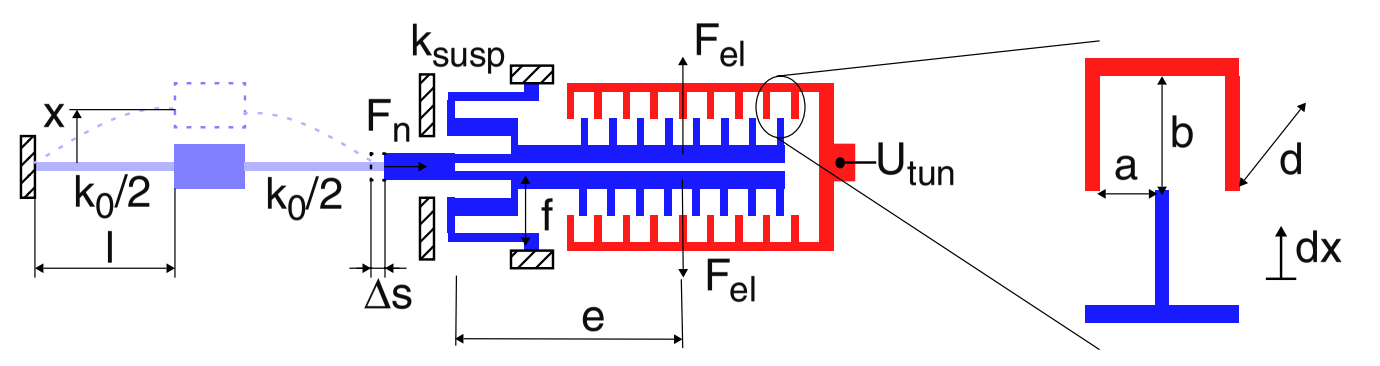


Figure 2. Extracted detail of a mass-spring resonator

- The sensor was simulated and optimized by FEM simulation during its development, but FEM simulation is too slow for system simulation.

  ⇒An abstract version was modeled and simulated in the VHDL-AMS hardware description language

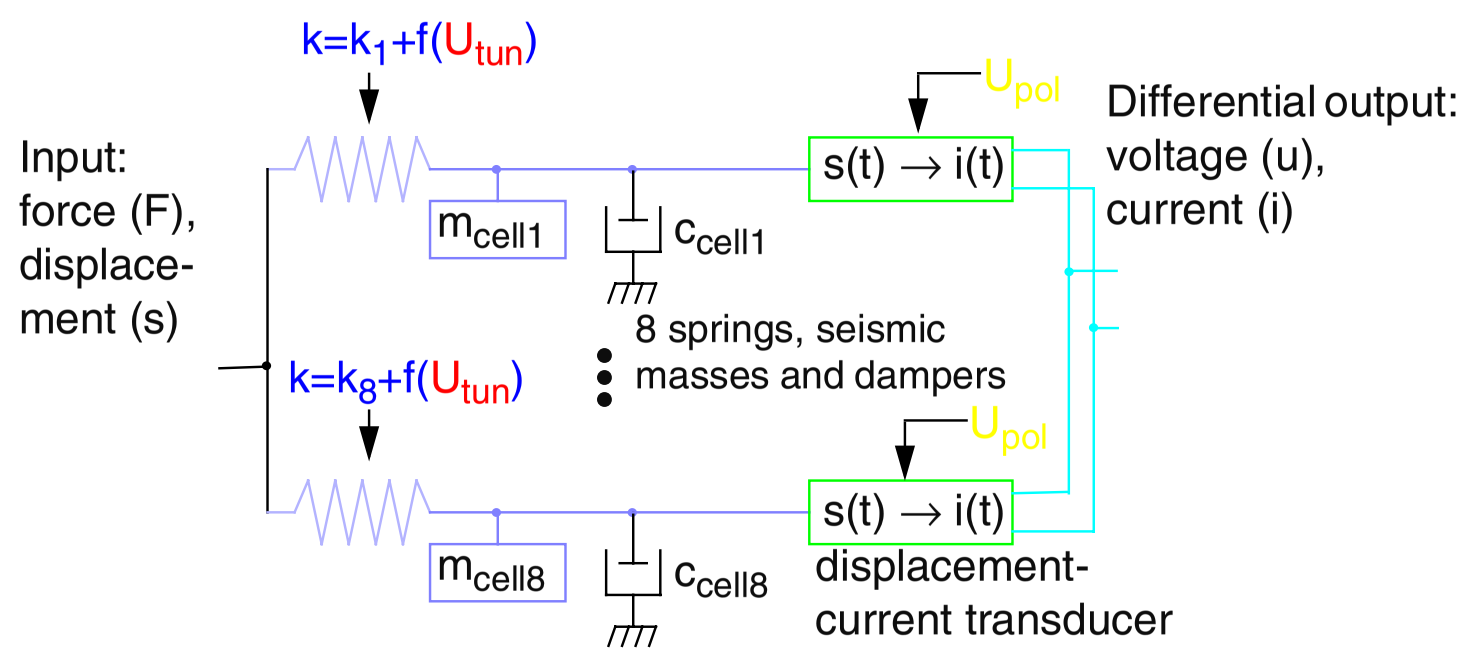


Figure 3. Schematic of the sensor array

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:

$$F_{el} = \frac{dW}{dx}, \qquad dW = \frac{1}{2} \cdot U_{tun}^{2} \cdot dC$$

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

$$C = 2n \cdot \varepsilon \cdot \frac{x_{ss} \cdot d}{a}, \qquad \frac{dC}{dx} = 2n \cdot \varepsilon \cdot \frac{d}{a}$$

$$F_{el} = U_{tun}^{2} \cdot \frac{n \cdot \varepsilon \cdot d}{a}$$

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

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

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
  k==k0+12.0/5.0*fn/l;                          --actuators per spring

  f==k*x;
END;
```

Tuning by an electrostatic spring

Tuning by stress-stiffening has two disadvantages.

- Fabrication of this structure is difficult because of stress in the layers,
- Lever mechanism is causing non-linearities in the behavior.

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.

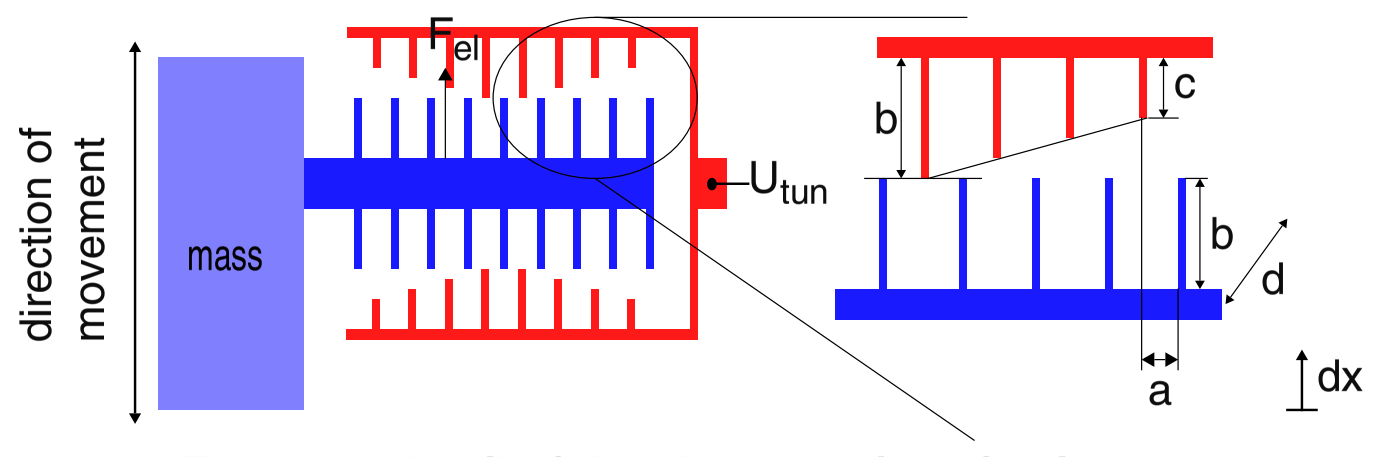


Figure 4. Extracted detail of the electrostatic softening

- Curve was optimized by FEM simulation.
- For system simulation it was assumed to be a linear function.

Figure 5. shows the structure of the VHDL-AMS sensor array model with this kind of tuning the natural frequency:

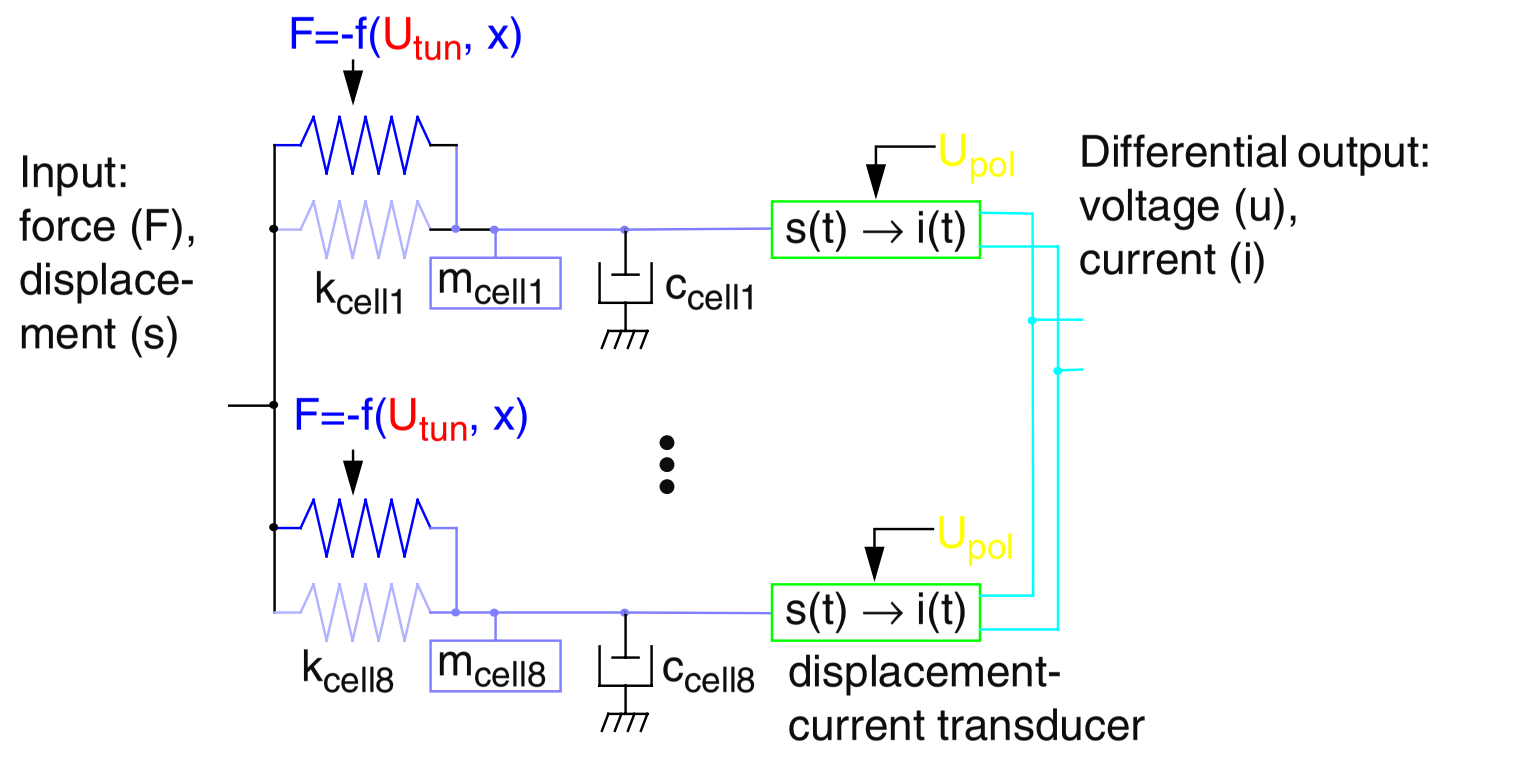


Figure 5. Schematic of the sensor with electrostatic softening

The force in the electrical field of this comb structure can be calculated as follows:

$$F_{el} = \frac{1}{2} \cdot U_{tun}^{2} \cdot \frac{dC}{dx}$$

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

$$C = 2 \cdot \varepsilon \cdot \frac{d \cdot x}{a} \cdot \frac{x}{b-c} \cdot n \cdot \frac{1}{2}, \qquad C = \varepsilon \cdot \frac{d}{a} \cdot x^2 \cdot \frac{n}{b-c}$$

$$\frac{dC}{dx} = 2 \cdot \varepsilon \cdot \frac{d \cdot x}{a} \cdot \frac{n}{b-c}$$

$$F_{el} = U_{tun}^{2} \cdot \varepsilon \cdot \frac{d \cdot x}{a} \cdot \frac{n}{b-c}$$

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

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

And in the range $|x| > (b-c)$ applies:

$$C = 2n \cdot \varepsilon \cdot \frac{(x-(b-c)) \cdot d}{a} + C_0, \qquad \frac{dC}{dx} = 2n \cdot \varepsilon \cdot \frac{d}{a}$$

$$F_{el} = U_{tun}^{2} \cdot n \cdot \varepsilon \cdot \frac{d}{a} \quad \text{for } x > (b-c)$$

$$F_{el} = -U_{tun}^{2} \cdot n \cdot \varepsilon \cdot \frac{d}{a} \quad \text{for } x < -(b-c)$$

Displacement-current transducer

The response of the structures is detected capacitively by comb electrodes at the seismic mass. The displacement-current transducer is also made of a curved comb structure which was optimized by FEM. For system simulation this curve was neglected because of the low curvature.

The currents caused by movement can be calculated by simplification of a homogeneous field of a capacitor as follows:

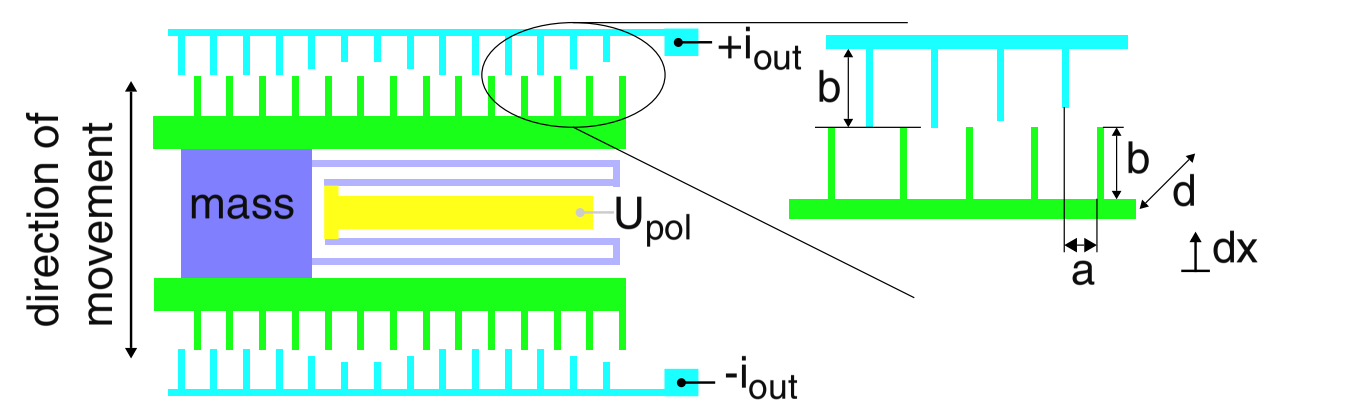


Figure 6. Displacement-current transducer

$$i(t) = U_{pol} \cdot \frac{dC}{dt}$$

$$C = 2n \cdot \varepsilon \cdot \frac{x \cdot d}{a}$$

$$\frac{dC}{dt} = 2n \cdot \varepsilon \cdot \frac{d}{a} \cdot \frac{dx}{dt}$$

$$i(t) = U_{pol} \cdot 2n \cdot \varepsilon \cdot \frac{d}{a} \cdot \frac{dx}{dt}$$

VHDL Source-Code of the Displacement-current transducer:

```
ENTITY x2i IS
  GENERIC (n,a,b,d,eps,lm:real);
  PORT ( TERMINAL t1:mech_F_s;
         TERMINAL i_p,i_m,v_pol:electrical);
END;

ARCHITECTURE behav OF x2i IS
  QUANTITY pos ACROSS t1;
  QUANTITY v: real;
  QUANTITY up ACROSS v_pol to i_p;
  QUANTITY un ACROSS v_pol to i_m;
  QUANTITY ip THROUGH i_p;
  QUANTITY im THROUGH i_m;
BEGIN
  v==pos'dot;
  ip== up*2.0*n*eps*d/a*v;
  im==-un*2.0*n*eps*d/a*v;
END;
```

Analog Signal Processing

Analog signal processing includes a current to voltage converter and a differential amplifier which amplifies the low output current from the transducer. The usage of a differential output avoids non-linearities of the output signal. The next part is a lock-in amplifier. This amplifier extracts the magnitude of the measured signal at a certain frequency.

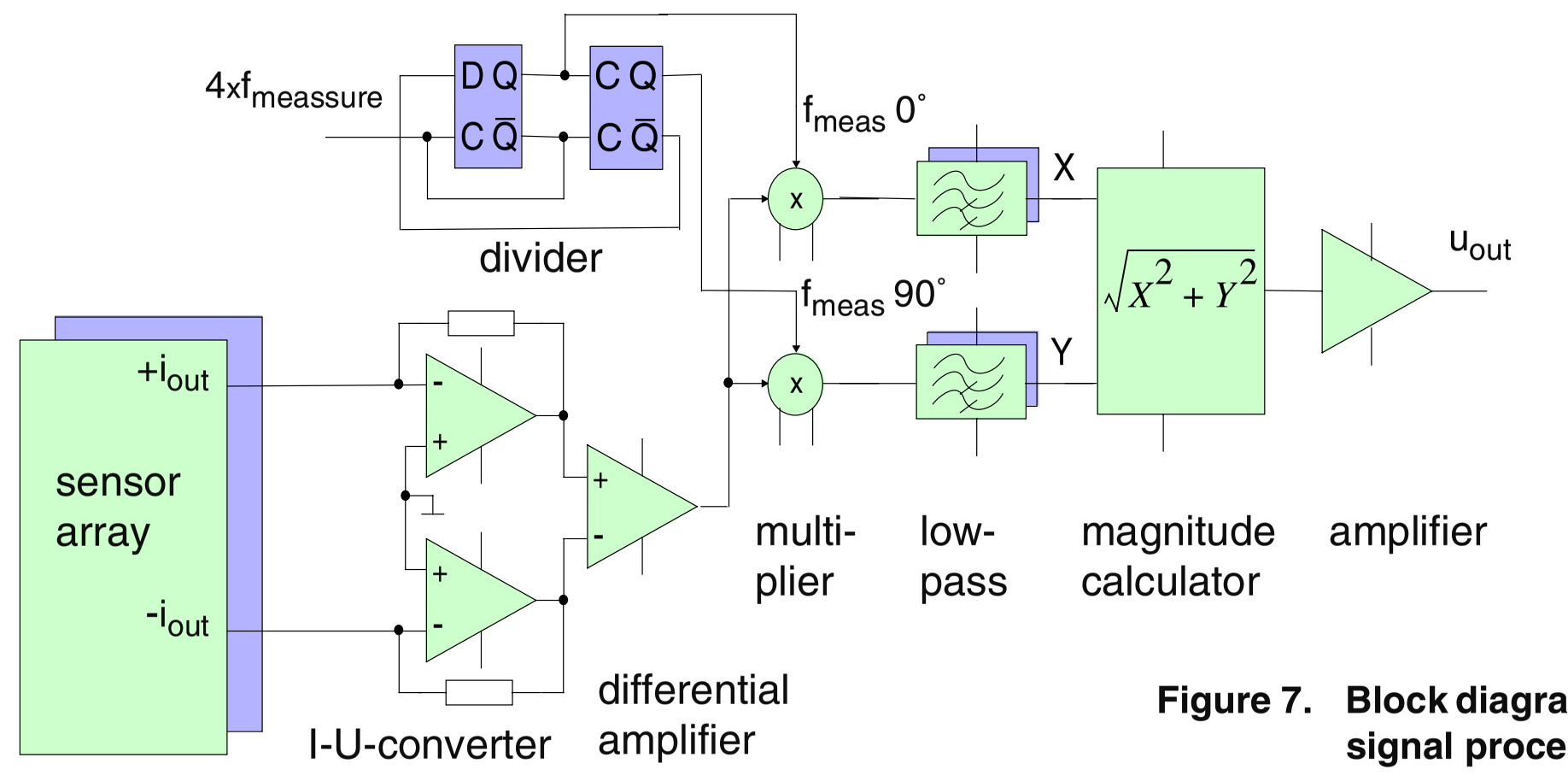


Figure 7. Block diagram of analog signal processing

For modeling this circuit a new design approach called **Multi Architecture Modeling** was used (for details see next section). The components were designed as functional blocks firstly. By using conservative nodes (*terminal*) and by insertion of power supply nodes even at this high abstraction level it is possible to exchange these abstract components partly or completely against models of real electrical elements.

Special Modeling Methods

Deferred constants

- Even in a small model the parameter list (*generics*) may contain numerous items.
- A *generic* list for the complete sensor model would contain about 50 items, but 50 parameters in a *generic* are very confusing.

⇒ The solution of this problem is to use deferred constants.

- The parameters of the sensor are declared as a *constant* in a *package* without a default value.
- The default values of the constants are assigned in the *package body*.
- By using deferred constants the value of the constant can be modified in the *package body* without the need to recompile anything else than the *package body*.

Multi architecture modeling

Digital, analog electrical and non-electrical models at different abstraction levels may appear during the design process. The abstraction level of these interfaces depends on the abstraction level of the component.

If system models are developed within the scope of a system design then it could have been necessary until now to modify the interfaces of the system and component models at every design step of a component model.

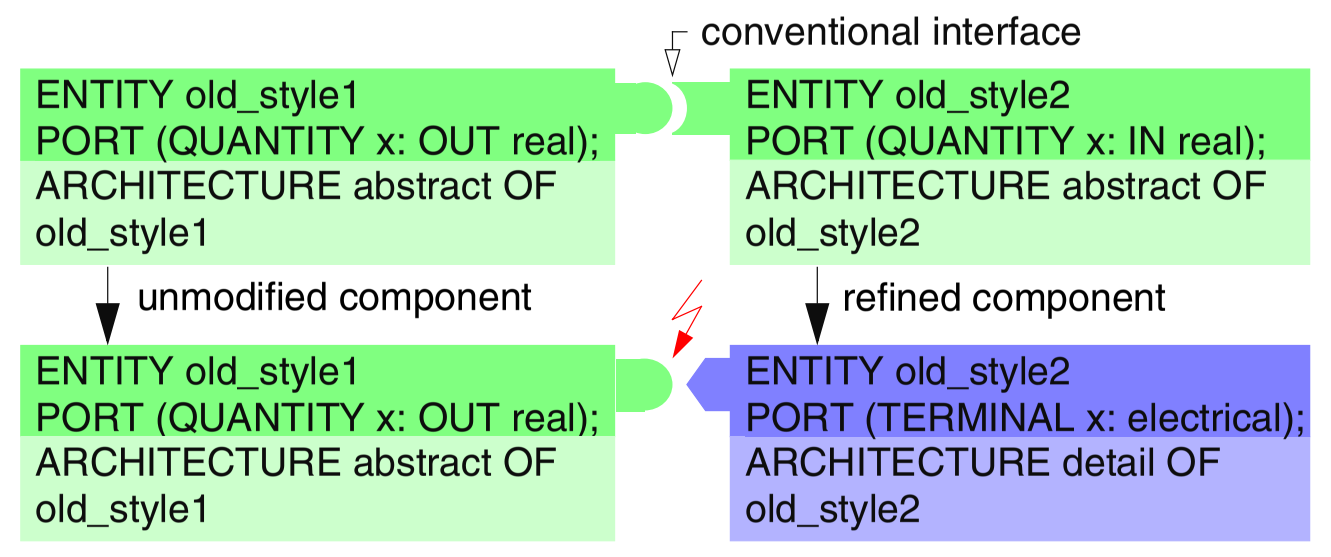
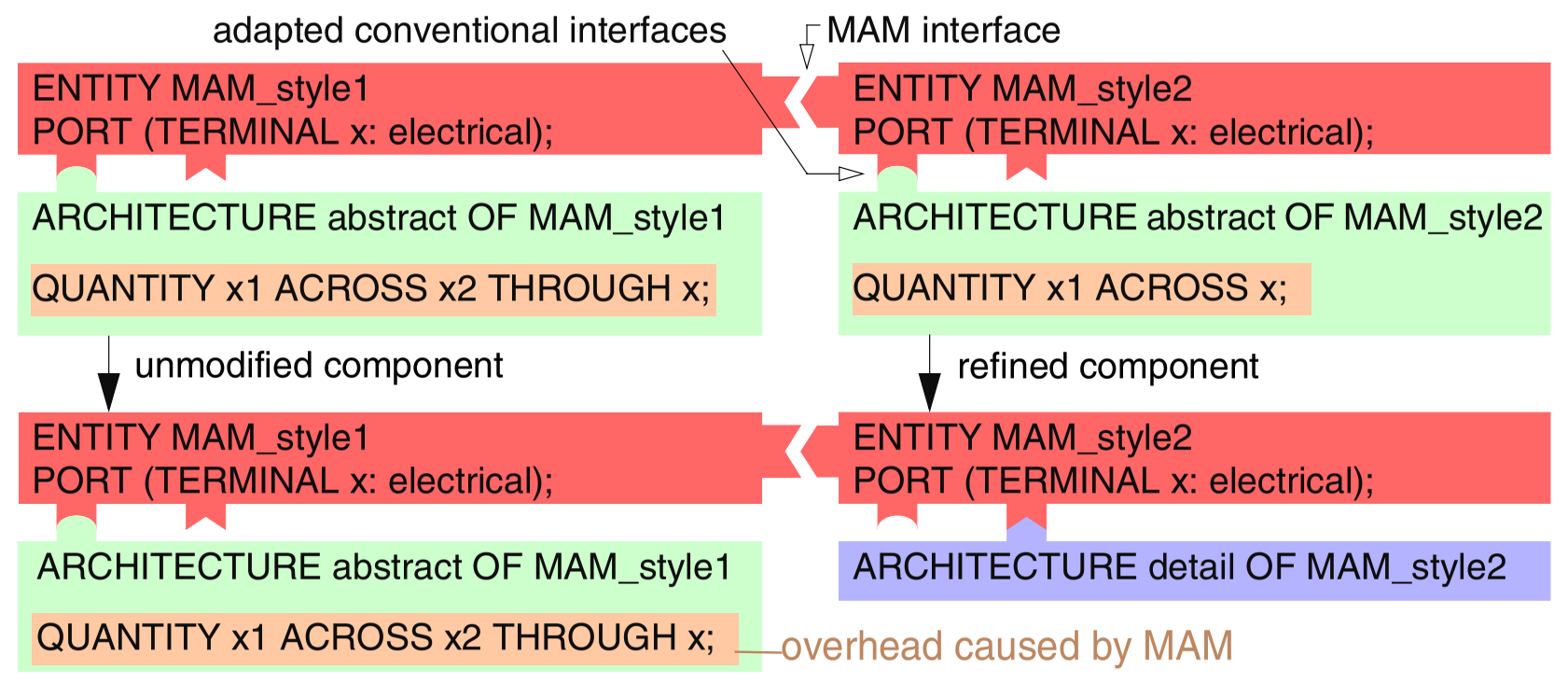


Figure 8. Possible problem during conventionally top down design process due to different interface objects



A possible solution of this problem is the Multi Architecture Modeling (MAM):

The main idea of MAM is to use the interface, which will be necessary at low abstraction level, already at a high abstraction level. This avoids a lot of work because abstract models of a component can be replaced by detailed models or vice versa without any modification to the interface or the surrounding models.

Figure 9. Unified interface for analog models using MAM

The domain for translatory movement

- If the design of mechanical components is done by an analogy transformation to electrical systems the *across* and *through quantity* is limited to velocity and force as analogy to voltage and current.
- In opposition to this, VHDL-AMS allows the description of mechanical behavior without analogy transformation.
- Measurement of vibration is normally done by measuring accelerations. So it was obvious to model the mechanical parts with acceleration and force. This is no problem until a resulting velocity or displacement is needed.

As is generally known:

$$v = \int a dt + C_0, \qquad s = \int v dt + C_1$$

The integration constants C_0 and C_1 cause difficulties - they cannot be set explicitly by the VHDL-AMS `'integ` attribute. This, e. g., results in:

$$a = A \cdot \sin(\omega t)$$

$$v = A \cdot \int \sin(\omega t) + C_0 = -\frac{A}{\omega} \cdot \cos(\omega t) + C_0$$

The simulator assumes:

$$v(0) = -\frac{A}{\omega} \cdot \cos(0) + C_0, \qquad C_0 = \frac{A}{\omega}$$

This results in an offset of the calculated velocity which will be integrated when calculating the displacement. This means that in the simulation the sensor „pulls the machine tool away“.

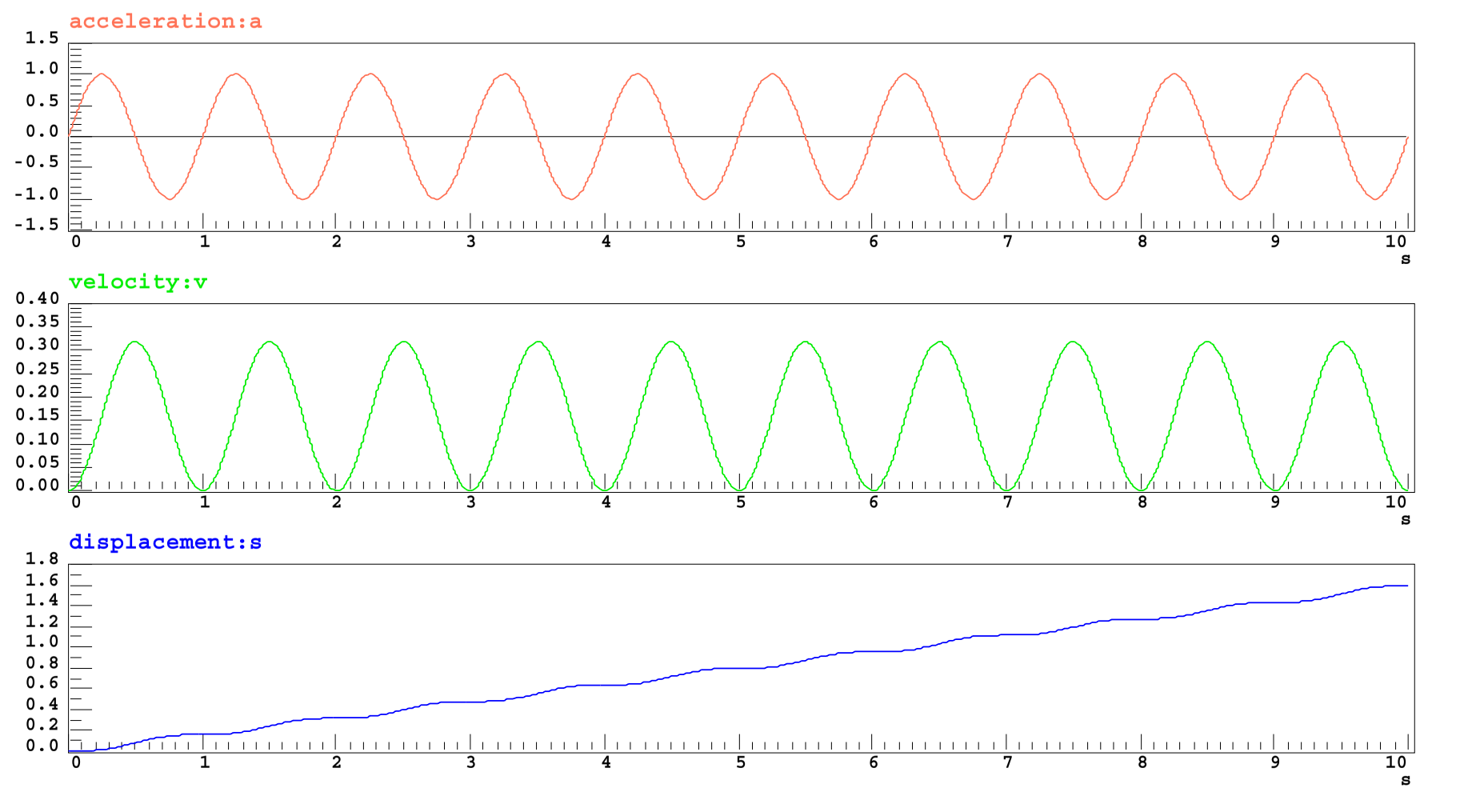


Figure 10. Simulation plot of a twice integrated sinusoidal acceleration

The solution of the problem is to use displacement as *across quantity*. If a velocity or acceleration is needed then these values can be calculated definitely by derivation of displacement over time. The measured vibration data must be converted into displacement data but this can be done easily.

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. The red graph shows the spring constant as a function of the tuning voltage with tuning by stress-stiffening effect. It can be seen easily that the spring constant increases with tuning voltage.

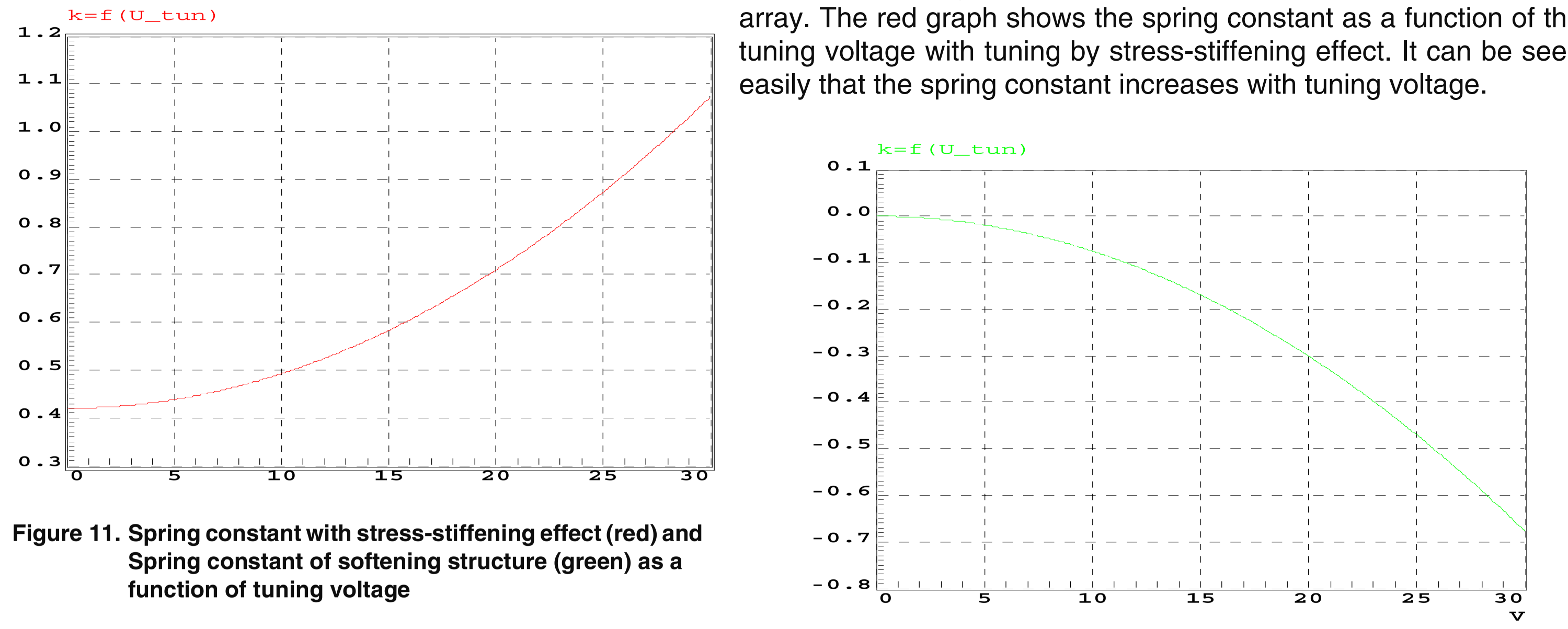
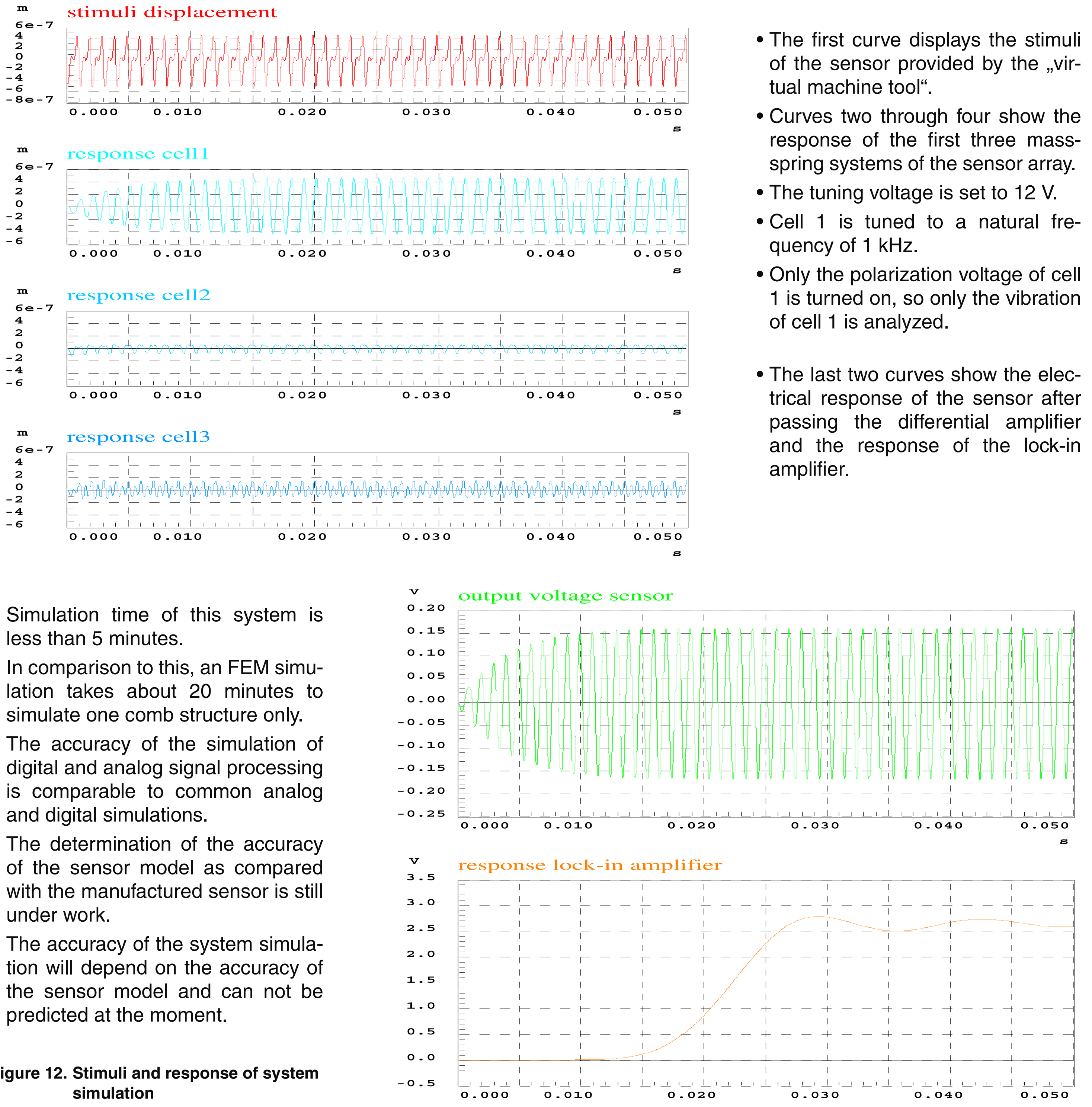


Figure 11. Spring constant with stress-stiffening effect (red) and Spring constant of softening structure (green) as a function of tuning voltage

The green graph shows the spring constant of the electrostatic softening structure. It can be seen that the spring constant assumes a negative value. This means that this spring will produce an attraction force when it is being compressed. In opposition to this a normal spring would produce a repulsion force if 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 5.) and so the spring constant of this structure can be modified by tuning voltage.

- Simulation time: 1 second
- Simulation inaccuracy:
  - softening structure: 4 % as compared with the FEM simulation
  - stress-stiffening structure: about 10 % as compared with the FEM simulation

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. The next figure shows the simulation results.



- 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.
- Cell 1 is tuned to a natural frequency of 1 kHz.
- Only the polarization voltage of cell 1 is turned on, so only the vibration of cell 1 is analyzed.
- The last two curves show the electrical response of the sensor after passing the differential amplifier and the response of the lock-in amplifier.

- 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.
- The accuracy of the simulation of digital and analog signal processing is comparable to common analog and digital simulations.
- The determination of the accuracy of the sensor model as compared with the manufactured sensor is still under work.
- The accuracy of the system simulation will depend on the accuracy of the sensor model and can not be predicted at the moment.

Figure 12. Stimuli and response of system simulation

Advantages of using VHDL-AMS

- Components can be modeled in the mechanical domain directly without any analogy transformation, e. g. the behavior of a spring can be described as $F = k \cdot s$ (force, spring constant, displacement).
- It is possible to describe every linear and most nonlinear behavior between force and acceleration, velocity or displacement.
- Mechanical behavior can be described and simulated together with analog and digital electrical behavior.
- Fast simulation
- Models can be scaled between speed and accuracy.
- Models are described in an international standardized language, models are independent of a simulator.

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 by using a hardware description language an interactive optimization of the system is possible, and also the interaction between the components can be tested easily. Although the abstraction of the behavior is quite high the accuracy of simulation is pretty good.

At the moment the models for the whole experimental prototype „vibration sensor array“ are not yet complete. The digital components „control“ and „fuzzy pattern classification“ still have to be implemented. When this is done it will be possible to simulate whole measurement cycles in relative short times.

Contact

Michael Schlegel, Göran Herrmann, Dietmar Müller
Chemnitz University of Technology,
Faculty of Electrical Engineering and Information Technology,
D-09126 Chemnitz, Germany

e-mail: michael.schlegel@infotech.tu-chemnitz.de
Tel.: +49 371 531 3158
Fax: +49 371 531 3186
WWW: http://www.infotech.tu-chemnitz.de/~sse

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