

Combining Models of Physical Effects for Describing Complex Electromechanical Devices

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Abstract

In contrast to classical object-oriented electromechanical modeling, i.e. describing plates, suspensions, drives etc. [4], this paper proposes to combine models of basic physical effects to object models which in turn can be used for system modeling. This allows to freely choose which effects are to be considered for some simulation. Moreover, the development of new object models is simplified. The paper shows how to model a wide variety of electromechanical devices with a well-defined library of basic effects.

Keywords: *gyroscope; analytical modeling; mixed technology; electromechanical effects; VHDL-AMS.*

Introduction

Complex mechanical devices can be modeled with the finite element approach, which is also available in circuit simulators [1]. Unfortunately these models are not always suited for system simulation due to their computing effort. Usually, complete devices can not be modeled with one finite difference or analytical model, which would be easy to implement in an analog hardware description language. To overcome these problems, the components of the mechanical device are modeled separately and the complete behavior of the device is described by combining the models of its components, see [4].

For object oriented modeling, the devices are dismantled into masses, springs and dampers. For example an acceleration sensor could be dismantled into a seismic mass and a spring, which represents the suspension of the mass.

The physical effect approach goes one step beyond the object-oriented method. Its basic idea is to model effects which occur in or between electromechanical structures. These basic effect models are combined to object models, e.g. plate, suspension or drive models. For example, one could dissect the seismic mass in an accelerator sensor into the inertial effect of the mass, a capacity effect between the mass and it's

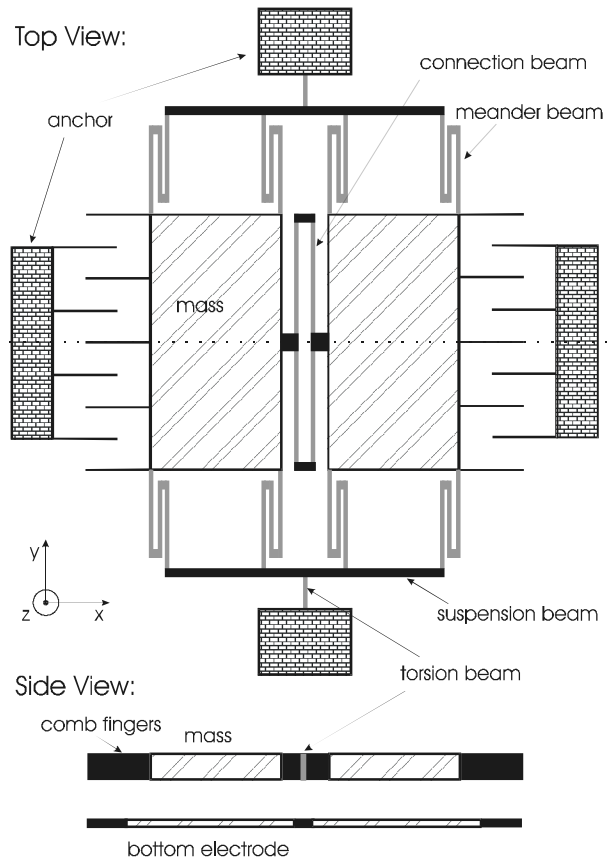


Fig. 1: Basic sketch of gyroscope

surrounding and an electrostatic effect between the mass and some detection electrode. The advantage of this kind of modeling is that the designer can decide which effects are necessary and which effects can be neglected. So he is able to choose the best trade-off between simulation accuracy and speed.

A gyroscope is a good demonstrator to show the benefit of effect modeling since it is a complex structure and comprises a lot of different effects. This paper investigates the effects occurring in the demonstrator and its implementation in VHDL-AMS. After this, the gyroscope, constructed out of the modeled effects, is simulated.

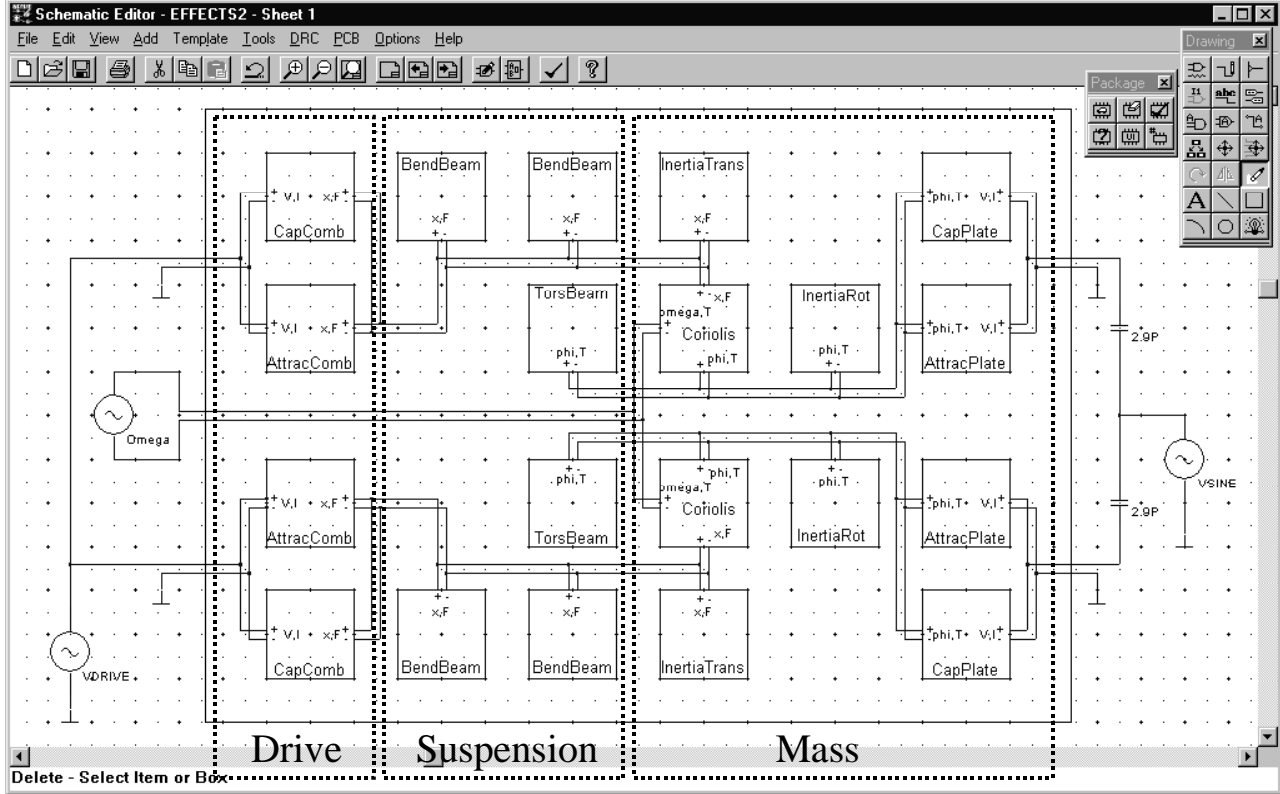


Fig. 2: Netlist of the gyroscope with basic test bench

Demonstrator: Gyroscope

The gyroscope is a combination of a sensor and an actuator. Two comb drives force an oscillation of two masses in the plane direction with is opposite in phase. The Coriolis effect causes a tilting of the two plates if an angular velocity occurs. The tilting of the masses results in a capacity change between a mass and its bottom electrode. So the angular velocity value can be detected by the capacity difference between the two plates with its bottom electrodes. Fig. 1 shows a basic sketch of the gyroscope. Fig. 2 displays the schematic of the gyroscope with some basic electrical components. Out of this schematic we could generate the mechanical netlist of the gyroscope, which comprises the basic effect models. Please note that this netlist respectively the schematic can be reduced by considering symmetries. The used effect models behind the symbols in Fig. 2 are described in the following.

Let us begin with the electrostatic attraction effect. A voltage, connected between two plates, induces an attractive force \vec{F} :

$$(1) \quad \vec{F} = \frac{dE}{d\vec{x}}$$

with electrical energy E and spatial coordinate vector \vec{x} . Solving this equation gives the results for the attraction force in the comb drive (AttracComb) and the attraction force induced by a readout voltage between the masses and its ground electrodes (AttracPlate).

The translational (InertiaTrans) and rotational (InertiaRot) inertia effect of masses calculates to

$$(2) \quad F = -m \frac{d^2}{dt^2} x$$

and

$$(3) \quad T = -J_A \frac{d^2}{dt^2} \varphi$$

respectively. With force F , mass m , displacement x , torque T , inertia moment J_A relating to turning point A and torsional angle φ .

The equation of Coriolis effect (Coriolis) is

$$(4) \quad T = 2m\omega x \frac{d}{dt} x$$

with angular velocity ω .

The bending effect of beams (BendBeam) can be calculated out of the following differential equation:

$$(5) \quad \frac{d^2 w_{(\xi)}}{d\xi^2} = -\frac{M_{(\xi)}}{EI_{(\xi)}}$$

with deflection w , bending moment M , elastic modulus E , inertia Moment I and position ξ .

The next differential equation describes the torsion effect in beams (TorsBeam):

$$(6) \quad \frac{d\phi_{(\xi)}}{d\xi} = \frac{T_{(\xi)}}{GI}$$

with rotational angle ϕ , torque T , sliding module G , torsional inertia Moment I and position ξ .

The capacity effect between two conductive structures influences a current i flowing through the structures:

$$(7) \quad i = C_{(\alpha)} \frac{d}{dt} v$$

where the capacity C depends on the displacement x in case of the comb drive (CapComb) or it depends on the rotational angle ϕ in case of the two tilting plates (CapPlate).

Implementation and Simulation

To make the effect models compatible with each other and to provide an easy extension of the model library, we have to carefully define suited ports for connection proposes. Table 1 shows the used “through” and “across” variables in each domain used by the chosen ports.

| type of variable | electrical network | rotational movement | translational movement |
|--------------------|--------------------|---|----------------------------------|
| "through"-variable | current i | torque T | force F |
| "across"-variable | voltage v | angle ϕ angular velocity ω | displacement x velocity v |

Table 1: Variable types of the implemented ports for each domain

In VHDL-AMS we are not restricted to pre-given variable types. VHDL-AMS provides a comfortable definition of user defined types. Listing 1 shows an extract of the package “translational_system” to show the implementation of the translational movement variables in Table 1.

```
PACKAGE translational_system IS
  ATTRIBUTE unit : string;
  ...
  SUBTYPE displacement IS REAL TOLERANCE
    "default_displacement";
  ATTRIBUTE unit OF displacement :
    SUBTYPE IS "m";
  SUBTYPE force IS REAL
    TOLERANCE "default_force";
  ATTRIBUTE unit OF force : SUBTYPE IS "N";
  NATURE translational IS
    displacement ACROSS
    force THROUGH
    translational_ref REFERENCE;
END PACKAGE translational_system;
```

Listing 1: VHDL-AMS implementation of user defined variables

To demonstrate the implementation of the effects, Listing 2 displays the used VHDL-AMS code of the Coriolis effect, see equation (4). Please note the very easy translation of mathematical models to VHDL-AMS description. So with VHDL-AMS, the modeling task is not an extra charge for the designer, thus contributing to reducing time-to-market.

```
USE work.translational_system.all;
USE work.rotational_system.all;

ENTITY Coriolis IS
  GENERIC (width, length, depth, roh: REAL);
  PORT (TERMINAL tran_p,tran_n:TRANSLATIONAL;
        TERMINAL rot_p, rot_n: ROTATIONAL;
        TERMINAL rot_om_p, rot_om_n:
          ROTATIONAL_OMEGA);
END ENTITY Coriolis;

ARCHITECTURE simple OF Coriolis IS
  QUANTITY pos ACROSS tran_p TO tran_n;
  QUANTITY torque THROUGH rot_p TO rot_n;
  QUANTITY omega ACROSS rot_om_p TO rot_om_n;
  CONSTANT mass : REAL :=
    width*length*depth*roh;
BEGIN
  torque == 2.0 * mass * omega * pos * pos'dot;
END ARCHITECTURE simple;
```

Listing 2: VHDL-AMS implementation of Coriolis effect

After describing the basic effects, the modeling and simulation of the gyroscope with some basic electronic components was done. For simulation we used the mixed signal and multi-level simulator SMASH¹. Fig. 3 displays the simulation results of netlist in Fig. 2. It shows the applied angular velocity, the translational displacement of one plate due to a driving voltage applying on the comb drives, the tilt angle of one plate and the capacity difference of both plates to their bottom electrodes. This capacity difference is a measure of the applied angular velocity and can be used in some further readout circuitry.

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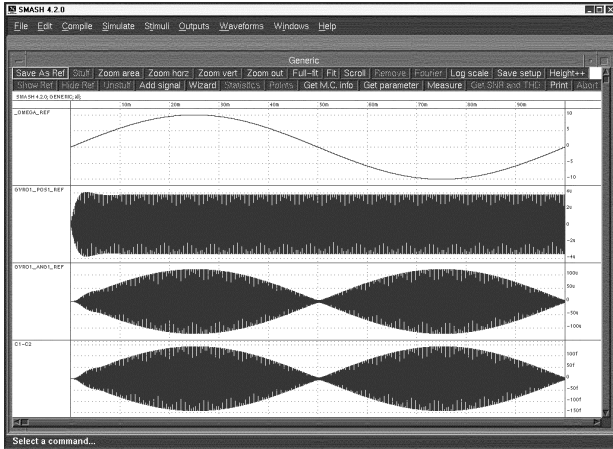


Fig. 3: Position (trace 2), angle (3) and capacity (4) in dependence on rotational velocity (1)

In the simulation of the gyroscope, some more attention has to be paid to possible simulator artifacts. Since the gyroscope is driven at its mechanical resonance frequency to get large displacements with relatively low driving voltage amplitudes, some damping has a strong influence. To reduce simulator intrinsic damping, simulation parameters have to be chosen for relatively high simulation accuracy.

We have compared the simulation results with finite element simulations and analytical equations. In an analytical validation, we have calculated the spring stiffnesses and masses of the gyroscope elements out of its geometrical dimensions and its material properties. With this data we have calculated the first resonance frequencies of the bending mode in drive direction and the torsional mode in detection direction. Comparing the analytical results with finite element modal analysis leads to corresponding resonance frequencies which are also confirmed by the physical effects simulation. Table 2 lists the calculated and simulated resonance frequencies for the two different excitation modes.

| | drive mode | detection mode | higher modes |
|-------------------|------------|----------------|--------------|
| analytical | 5714 | 5716 | |
| FEM | 5826 | 5914 | >12kHz |
| effect simulation | 5745 | 5760 | |

Table 2: Calculated and simulated resonance frequencies of the gyroscope

Conclusion and Outlook

The introduced model of the gyroscope can be easily extended with further effects like the effect of air damping. Moreover, with the same introduced effects, it is possible to model totally different devices like accelerometers or micro mirrors because the basic effects, like bending of beams or inertia effects of masses are the same.

The introduced models extend the model library of electrical circuit simulation tools with electromechanical effects, so a system simulation becomes easy.

The new standard hardware description language VHDL-AMS is best suited for modeling mixed domain simulation needs due to its flexible quantity handling and the easy implementation of mathematical equations.

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