IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

VerilogA and SpectreHDL MEMS Compact Model Library for the Spectre Simulator within Cadence

User Guide

Author: Jacopo Iannacci

Version: 1.0.4

Date (original version): 18/04/2007
Date (updated version): 14/02/2011

Fondazione Bruno Kessler – FBK
Centre for Materials and Microsystems – Irst
MEMS Research Unit
Via Sommarive 18, 38123
Povo, Trento, Italy
Email: iannacci@fbk.eu
URL: www.fbk.eu
http://memsrad.fbk.eu/en/home

The MEMS software library has been developed in collaboration with Dr. Roberto Gaddi and Prof. Antonio Gnudi, and with the ARCES Research Centre (University of Bologna, Italy).

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

1. Introduction

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

This document is a short user guide explaining how to properly use the MEMS compact model library available in VerilogA© and SpectreHDL© languages within the Cadence© environment for the Spectre© Circuit Simulator.

All the most important issues including the proper configuration of the library itself within the Cadence environment, the properties settings of each model together with the actual use of this tool, e.g. simple examples of MEMS structures and clues about how to face convergence problem, will be given through the following pages.

Moreover, being the library available in two different HDL-based languages, details which are different depending on the particular implementation will be kept separated and singularly explained both for the VerilogA and SpectreHDL version.

2. How to Configure the Library within Cadence

The MEMS compact model library is treated by Cadence as a standard design-kit. This means it has to be copied in a proper location of the file system which we suppose to be **"/users/OPUS".** If we now name the two libraries as **"MEMS_MODELER_CONTAINER_VerilogA"** and "**MEMS_MODELER_CONTAINER_SpectreHDL**",
the components within each of them will be seen as subdirectories of the two following paths: **"/users/OPUS/MEMS_MODELER_CONTAINER_VerilogA"**
and **"/users/OPUS/MEMS_MODELER_CONTAINER_SpectreHDL"**. The previous absolute paths must then be added to the "Library Path Editor" [1] within Cadence in order to make the two libraries visible and usable within Cadence together with the other preexisting libraries and design-kits (see Figure 1).

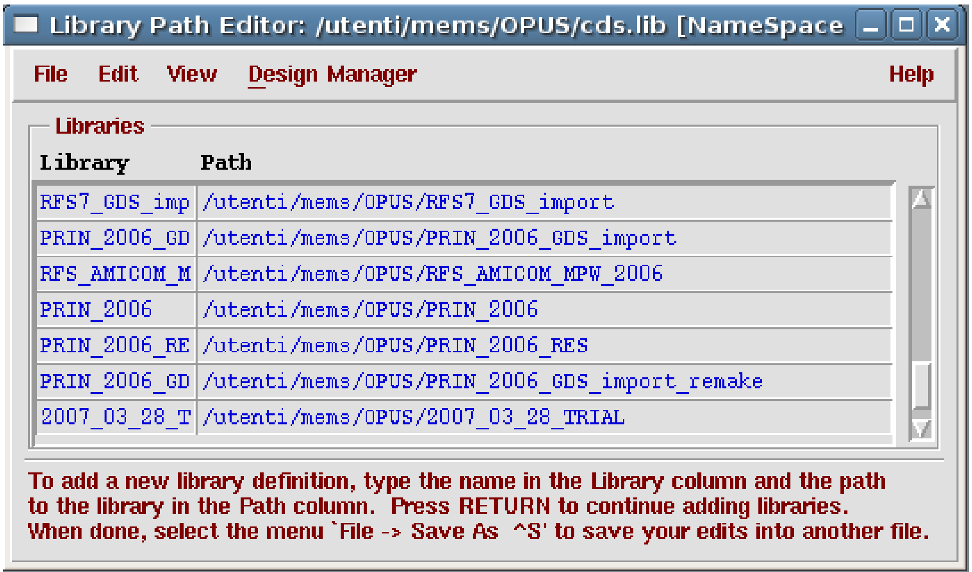

Figure 1: Library Path Editor window in Cadence. Once the library definitions are added the new configuration must be saved in the "cds.lib" file.

The MEMS compact models deal with mixed domain magnitudes, i.e. electrical and mechanical. Proper definitions for the electrical and mechanical magnitudes are declared within the libraries.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

Moreover, for each of them two parameters ("abstol" and "blowup") [2,3] used by the Spectre simulator to define convergence and non-convergence cases are defined for all the magnitudes. All the magnitudes with their physical meaning, name within Cadence, unit and parameter(s) value(s) are reported in Table 1.

Name within Cadence	Physical meaning	Unit	abstol	blowup
disp	Mechanical linear displacement	Meter (m)	1.0e-9	--
frc	Mechanical linear force	Newton (N)	1.0e-9	--
vel	Mechanical linear velocity	Meter/Second (m/s)	1.0e-3	1.0e+12
acc	Mechanical linear acceleration	Meter/Second^2 (m/s^2)	1.0e-3	1.0e+12
ang	Mechanical rotation	Radiant (rad)	1.0e-3	--
trq	Mechanical torque	Newton*Meter (N*m)	1.0e-3	--
avel	Mechanical angular velocity	Radiant/Second (rad/s)	1.0e-3	1.0e+12
aacc	Mechanical angular acceleration	Radiant/Second^2 (rad/s^2)	1.0e-3	1.0e+12
V	Voltage	Volts (V)	1.0e-6	1.0e+12
I	Current	Ampere (I)	1.0e-6	1.0e+12

Table 1: Summary of all the electrical and mechanical magnitudes definitions within the VerilogA and SpectreHDL library version.

- In the **VerilogA** library the implementation definitions of Table 1 are included in the file **"/users/OPUS/MEMS_MODELER_CONTAINER_VerilogA/discipline/discipline.h"** and no special settings are required to properly link such a file.

- In the **SpectreHDL** the implementation information of Table 1 are defined within the file **"/users/OPUS/MEMS_MODELER_CONTAINER_SpectreHDL/quantity.spectre"**.
  This file must be linked to make it visible during simulations. To do this a line containing the information on where the file is located must be added to the "**cds.lib**" file (absolute path: **"/users/OPUS/ cds.lib**") before the lines referring to the actual libraries and design-kits. In this case the line has to be as follows:
  "**DEFINE MEMS_MODELER_CONTAINER_SpectreHDL /users/OPUS/MEMS_MODELER_CONTAINER_SpectreHDL**".

3. How to Instance the Available Components

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

Each component within the library is described by a schematic. This allows to compose the object to be simulated by adding instances within a Cadence Composer Schematic window as it is usually done with standard libraries (see Figures 2 and 3). Components are then connected together by means of wires (see Figure 4).

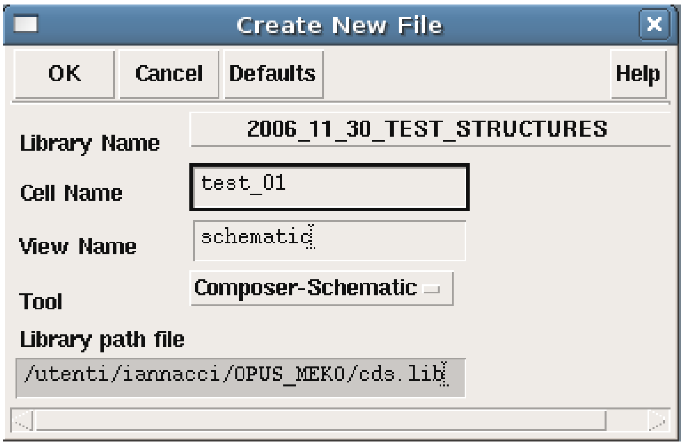

Figure 2: Definition of a new Composer Schematic file within an existing library.

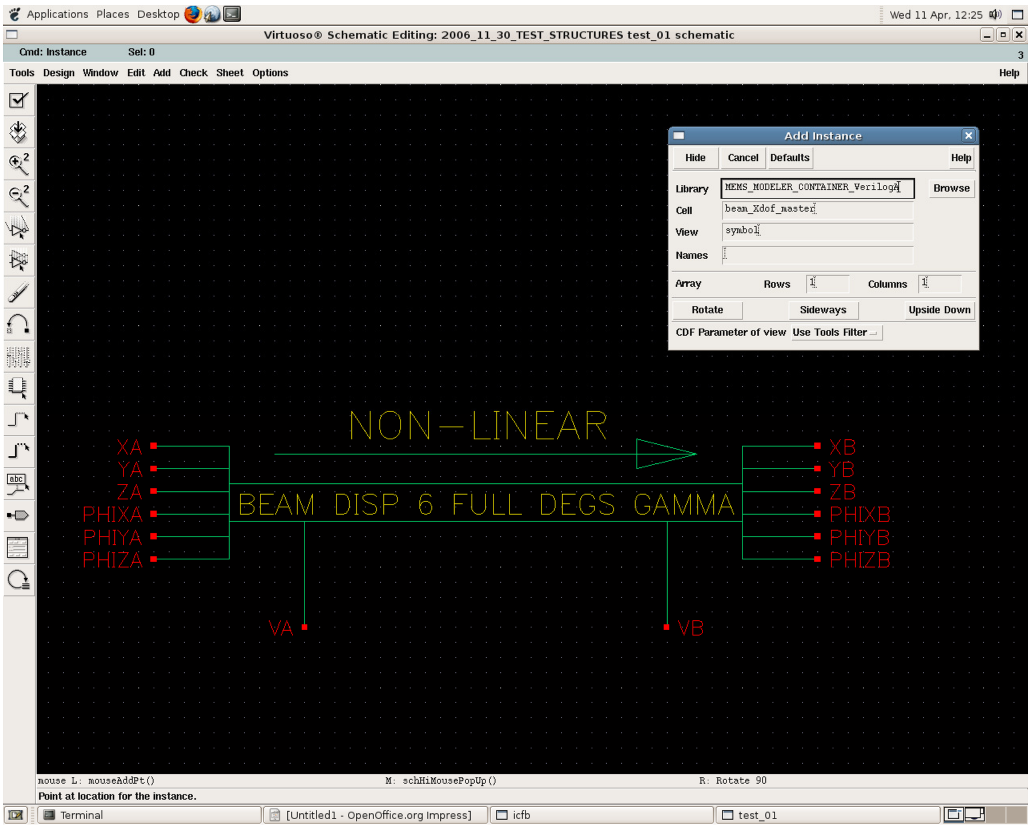

Figure 3: Instantiation of MEMS elementary components within the schematic window.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

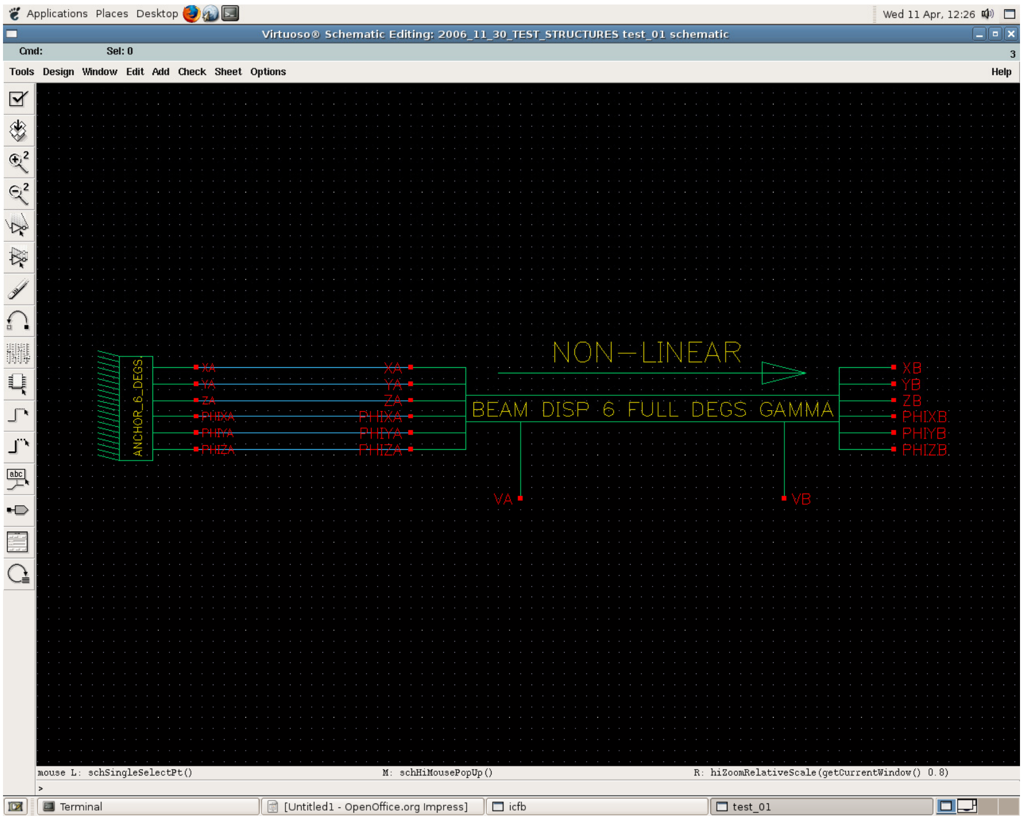

Figure 4: Connection of single components through wires.

4. The Flexible Straight Beam

With this section the description of each single device within the library starts. The first device is the flexible straight beam. The mechanical model includes 12 Degrees of Freedom (DOFs) i.e. three linear and three angular deformations at each beam end like the schematic of Figure 5 shows [4, 5].

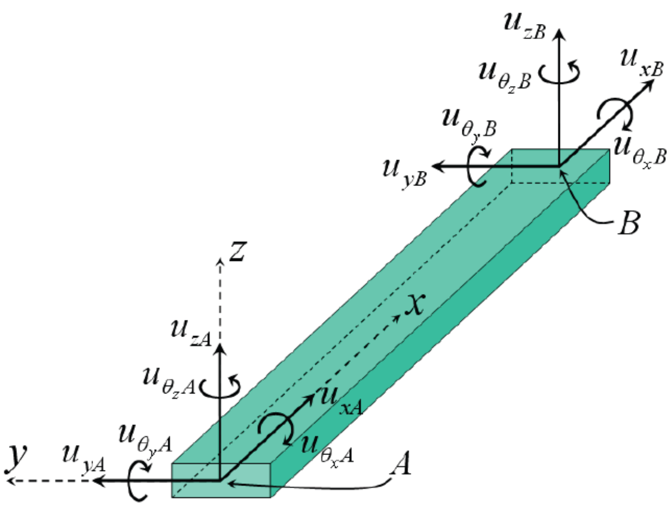

Figure 5: Schematic of the flexible straight beam with 6 DOFs at each end (A and B).

FONDAZIONE BRUNO KESSLER

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

It is possible to define a custom configuration of the components depending on the type of simulation that must be performed. The features selection will be shown soon. Every time a change is performed the component code must be re-compiled in order to allow Spectre to generate the proper netlist for the simulation. To do this, the main code file must be opened and saved within Cadence. Each component is defined in a subdirectory within the library. The 12 DOFs straight beam subfolder is "**beam_Xdof_master**" for both the library implementations. The main code file for the VerilogA and SpectreHDL is respectively located in the subsequent absolute paths: "**/users/OPUS/MEMS_MODELER_CONTAINER_VerilogA/beam_Xdof_master/veriloga/veriloga.va**"
and
"/users/OPUS/MEMS_MODELER_CONTAINER_SpectreHDL/beam_Xdof_master/ahdl/ahdl.def".
These files can be opened from the main Cadence window (File → Open) selecting the proper View Name (**"veriloga"** or **"ahdl"**) depending on the implementation. The case of VerilogA implementation is shown in Figure 6.

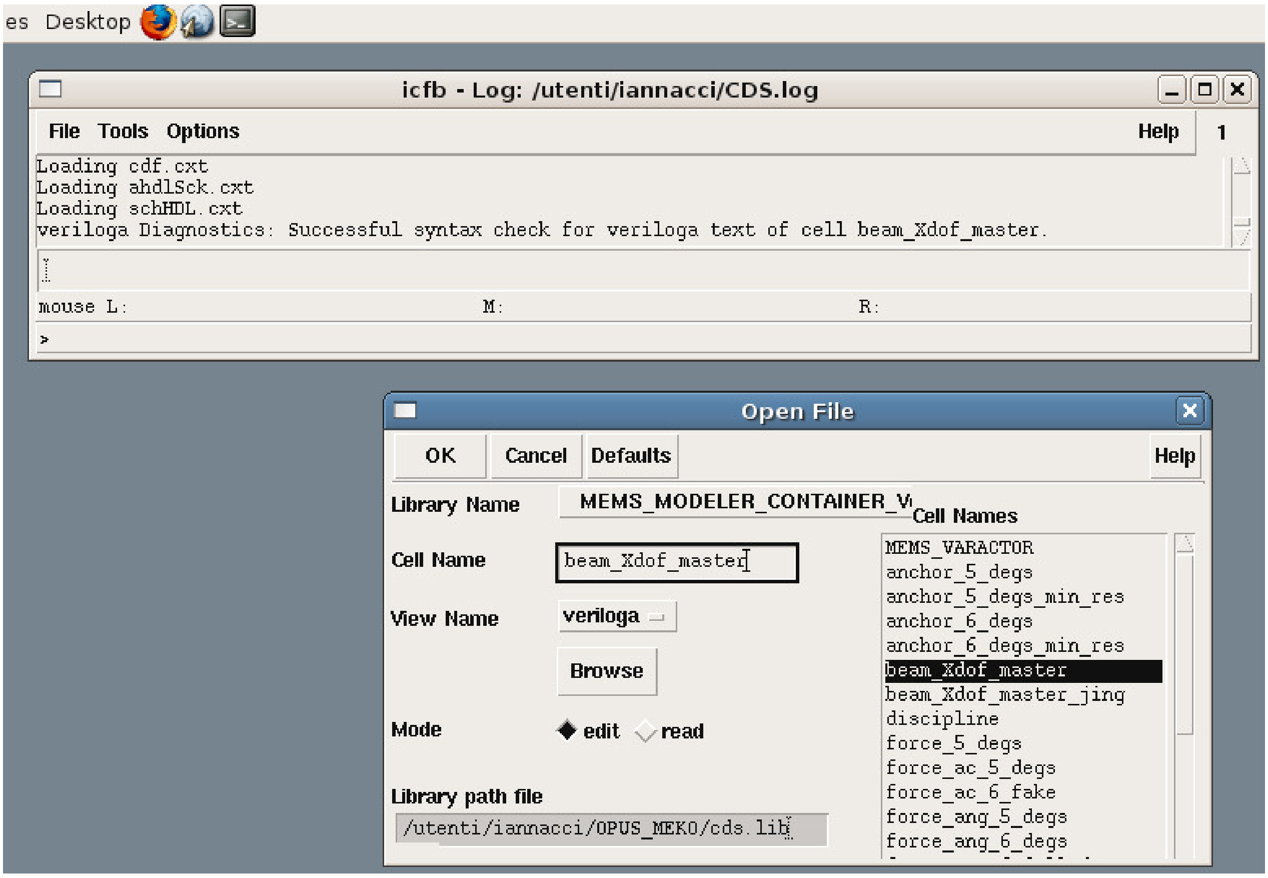

Figure 6: Proper opening of the main code file for the 12 DOFs beam. In the case of the SpectreHDL implementation the "View Name ahdl" has to be selected.

As a consequence a text editor window will open (usually **"vi"** Unix Editor). By saving and closing such a file the compilation will be automatically launched (in the case of **"vi"** the command to be typed is **":wq + Enter"** i.e. **w**rite and **q**uit shown in Figure 7).

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

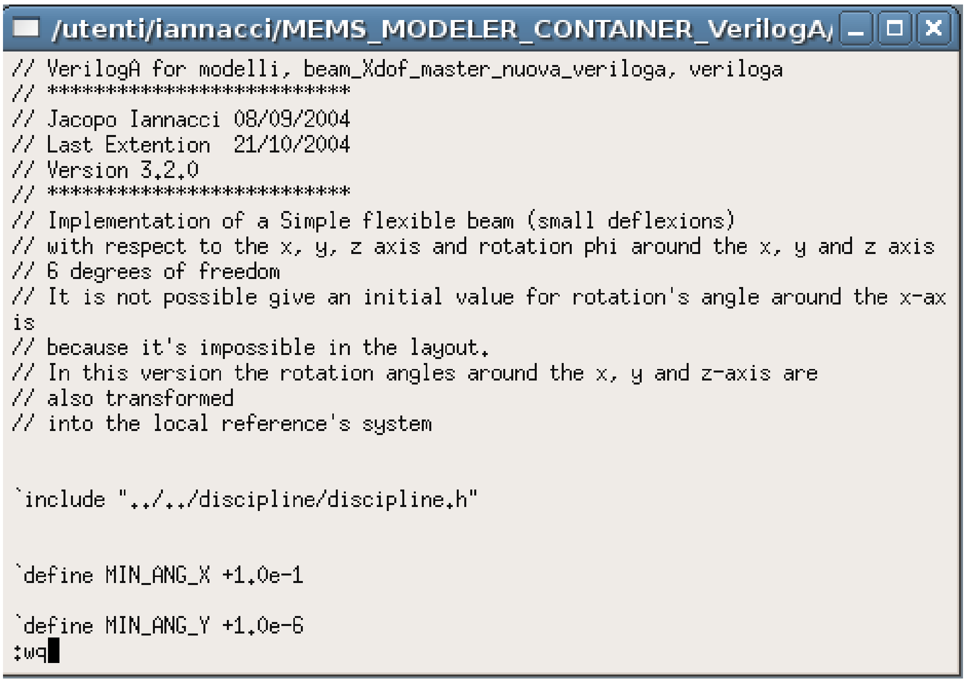

Figure 7: The command ":wq + Enter" i.e. write and quit launches the compilation of the file with the new features selection.

Features Definition

The list of all the possible features is contained in the file whose absolute path is: "**/users/OPUS/MEMS_MODELER_CONTAINER_VerilogA/beam_Xdof_master/main/main_beam.rgd**". Its content follows:

```
/// ******************************************************************* ///
/// MODULES INCLUSION. DEFINITION OF A CUSTOM BEAM'S MODEL FOR SIMULATIONS. ///
/// ******************************************************************* ///

// If parameters' values are set to 1 the corresponding module is included
// in beam's model, else, if value is equal to 0, is not included


//`define Rotation_Matrix_Modified

//`define Non_Linear_Deformations

//`define DC_Simulation_Model_Reduction

`define Shear_Effects

`define Contact_Effects

`define Electrostatic_Force

`define Capacitance
```

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

```
`define Apart_Electrodes

//`define No_Torsion_Around_X

`define Viscous_Damping

/// ********************************************************************** ///
/// -------------------- END OF THE MODULES INCLUSION --------------------- ///
/// ********************************************************************** ///
```

It is constituted by a series of **macro** variables definition. When a variable is defined it assumes a **TRUE** value (which means that the corresponding line is not commented i.e. it does not begin with the comment operator "//") and the corresponding feature is included in the code compilation. Whereas, when a variable is commented it is not defined and consequently the compiler query will return a **FALSE** value. In this case the feature defined by that variable will not be included in the model.

In the case of the SpectreHDL implementation this file is located as follows: **"/users/OPUS/MEMS_MODELER_CONTAINER_SpectreHDL/beam_Xdof_master/main/main_beam.rgd"** and its content is:

```
/// ********************************************************************** ///
/// MODULES INCLUSION. DEFINITION OF A CUSTOM BEAM'S MODEL FOR SIMULATIONS. ///
/// ********************************************************************** ///

// If parameters' values are set to 1 the corresponding module is included
// in beam's model, else, if value is equal to 0, is not included


#define Rotation_Matrix_Modified 0

#define Non_Linear_Deformations 0

#define DC_Simulation_Model_Reduction 0

#define Shear_Effects 1

#define Contact_Effects 1

#define Electrostatic_Force 1

#define Capacitance 1

#define Apart_Electrodes 1

#define No_Torsion_Around_X 0

#define Viscous_Damping 1

/// ********************************************************************** ///
/// -------------------- END OF THE MODULES INCLUSION --------------------- ///
/// ********************************************************************** ///
```

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

In this case a numeric value is associated to each **macro** variable definition and "**0=FALSE**" while "**1=TRUE**". Note that the configuration of the main inclusion file is the same for the two implementations of the 12 DOFs beam. We will now go through each of the variables definition explaining their meaning.

VARIABLE NAME	CORRESPONDING FEATURE
Rotation_Matrix_Modified	Defines a different analytical implementation for the rotation matrix compatible with large deformations [6]. **NOTE:** This feature is not tested and the variable should be left at the FALSE value.
Non_Linear_Deformations	Defines an analytical implementation accounting for the material non-linearities when large deformations occur [6]. **NOTE:** This feature is not tested and the variable should be left at the FALSE value. In most cases the beam deformations are small enough to make the linear mechanical model still suitable to reach a good predictive accuracy.
DC_Simulation_Model_Reduction	When set TRUE cuts out of the compilation all the definitions of dynamic nodes (i.e. time derivatives). **NOTE:** Makes the model more robust against convergence problems but can be used only for static DC simulations, as all the dynamics due to inertia and viscous damping are ignored.
Shear_Effects	When set TRUE includes the shear effects in the linear mechanical model [7]. **NOTE:** Should be always set TRUE.
Contact_Effects	When set TRUE includes the presence of the substrate underneath the beam i.e. includes the collapse of the beam on the substrate. **NOTE:** If set FALSE none of the following features can be included.
Electrostatic_Force	When set TRUE includes the electrostatic attractive force between the beam and the substrate when a bias voltage is applied between them.
Capacitance	When set TRUE enables the calculation of the capacitance between the suspended beam and the underlying substrate.
Apart_Electrodes	When set TRUE enables the definition of separated electrodes along the beam length (see Figure 10).
No_Torsion_Around_X	When set TRUE ignores the torsion around the X-axis along the beam length (see Figure 5) in

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

	the electrostatic magnitudes calculation and in the viscous damping effect. **NOTE:** It can be reasonably left FALSE as torsion around X is usually small.
Viscous_Damping	When TRUE includes the dynamic effect of the squeeze film damping which counteracts the beam movements [8].

Table 2: Summary of all the features which can be modified in the 12 DOFs beam model.

When the features selection corresponds to the one shown above in the "**main_beam.rgd**" file (for both the VerilogA and SpectreHDL implementations) the parameters which are accessible through the "**Edit Object Properties**" windows (reachable by selecting the beam schematic and typing "**Q**") are reported in Figure 8.

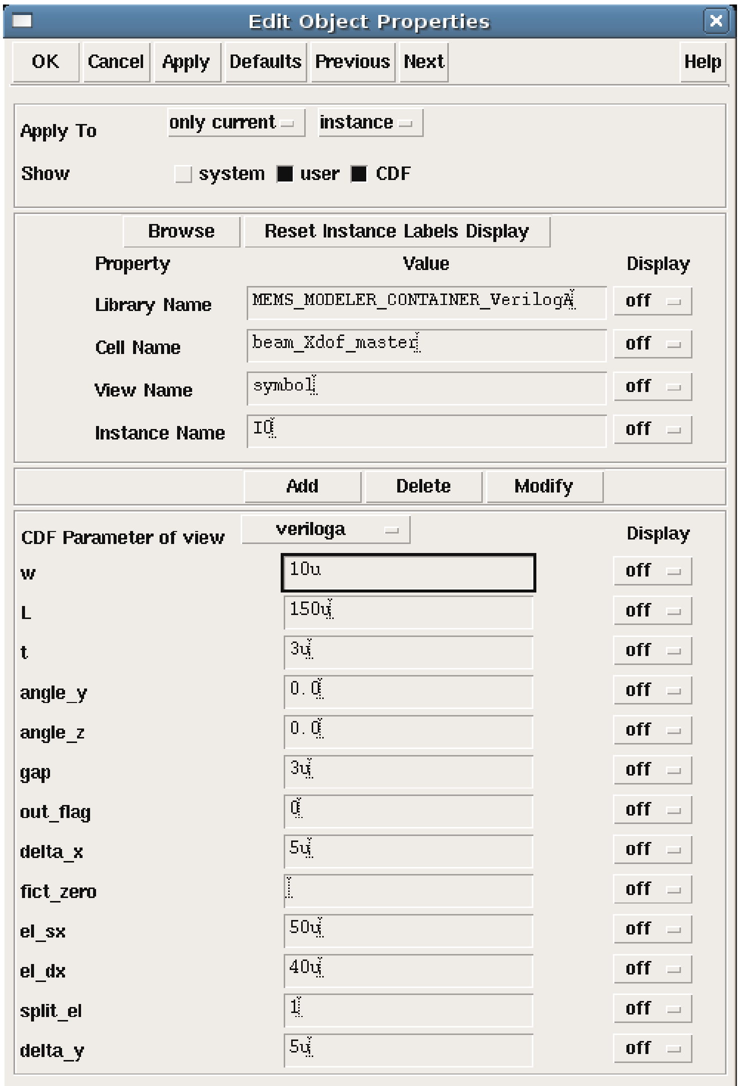

Figure 8: Object Properties mask for the 12 DOFs flexible beam with the features described above in the "main_beam.rgd" file. In the case of SpectreHDL the "CDF Parameter of view ahdl" must be chosen.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

The meaning of each parameter in previous mask (Figure 8) is listed in subsequent Table 3.

PARAMETER	MEANING
w	Beam width along the Y-axis (see Figure 5). In the case of Figure 8 is equal to 10 µm.
L	Beam length along the X-axis (see Figure 5).
t	Beam thickness along the Z-axis (see Figure 5).
angle_y	Initial beam orientation angle (in degrees) around the Y-axis (see **Clue 1**).
angle_z	Initial beam orientation angle (in degrees) around the Z-axis (see **Clue 1**).
gap	Vertical distance between the suspended beam and the underlying substrate.
out_flag	Boolean flag. If set to "1" displays real time information about the electrostatic force and capacitance values during the simulation.
delta_x	In the electrostatic magnitudes calculation the beam length is divided into an integer number of rigid non-parallel plates (see Figure 9). The parameter "**delta_x**" defines the length of each of these elements.
fict_zero	Value considered as fictitious zero in order to avoid division by zero. **NOTE:** When nothing is specified in the mask it is set to 1e-6 by default. This value usually does not need to be modified.
el_sx	Defines the length of the left portion of electrode (see Figure 10).
el_dx	Defines the length of the right portion of electrode (see Figure 10).
split_el	Defines the splitting scheme of the electrodes defined by the previous two parameters (see Figure 10). When "**split_el=1**" the electrode is placed in the area not covered both from "**el_sx**" and "**el_dx**". Differently, when "**split_el=0**" the electrode is on the area covered by "**el_sx**" and "**el_dx**".
delta_y	Corresponds to "**delta_x**" but define the sub-elements length along the Y-axis.

Table 3: Summary of all the parameters in the 12 DOFs beam Properties mask.

Clue 1

Misunderstandings can rise among orientation angles values within the mask of Figure 8 and the position of the beam schematic in the Composer windows of Cadence (see Figure 3). Actually, whatsoever rotation of the schematic **does not** implies a corresponding rotation of the beam within the structure to be simulated. These rotations are indeed defined through the "**angle_y**" and "**angle_z**" parameters defined above. It helps to maintain a logical link between the orientation of the schematic and the values of the latter parameters. For instance, if "**angle_z=90°**" the beam schematic should be rotated of 90° counterclockwise. Differently, if "**angle_z=-90°=270°**" the beam schematic should be rotated of 90° clockwise.

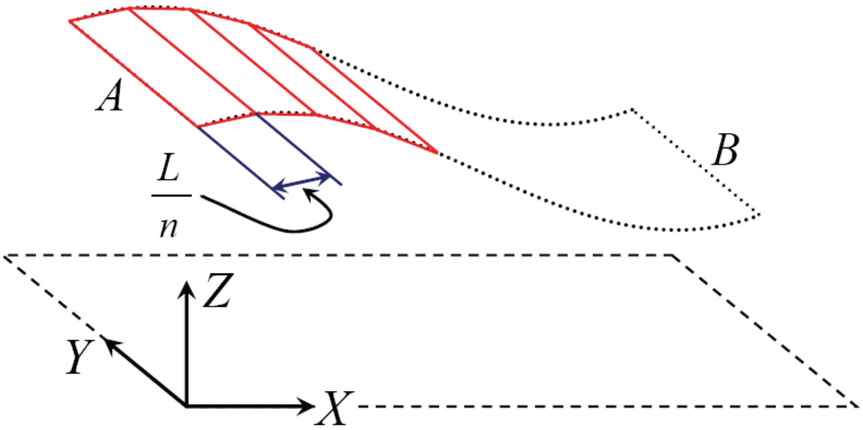

Figure 9: To carry out electrostatic calculations the beam length (L) is divided into an integer number (n) of sub-elements of length L/n treated as non-parallel rigid plates to the substrate.

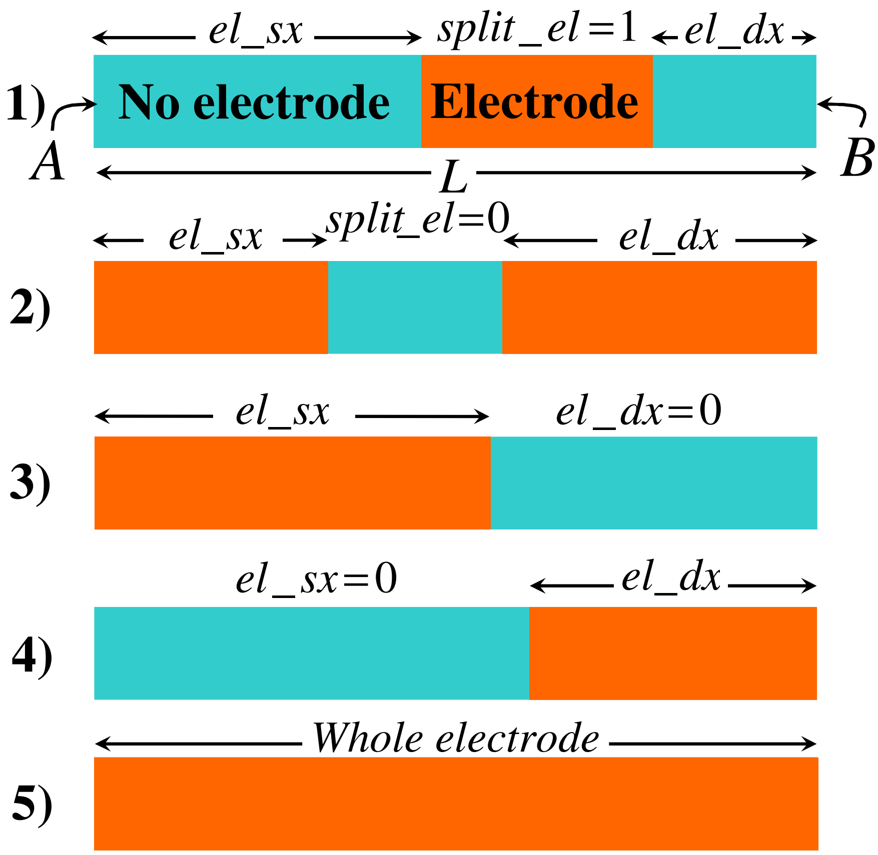

Figure 10: Possible configurations for the electrode(s). When "Apart_Electrodes" of Table 2 is FALSE the electrode is unique and placed over all the beam surface (case 5).

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

Material Characteristics

The material properties as well as several constants can be modified to adapt the beam model to the technology specifications. Both in the VerilogA and SpectreHDL implementations there is an header file defining which other files containing the technology and constants definitions must be included. Its absolute path is:
"**/users/OPUS/MEMS_MODELER_CONTAINER_VerilogA/qunatities/quantities.tf"** and
"**/users/OPUS/MEMS_MODELER_CONTAINER_SpectreHDL/qunatities/quantities.tf".**
Only the case of the VerilogA implementation is being shown as the approach is the same for the SpectreHDL version.

The content of **"quantities.tf"** follows:

```
// ***************** //
// ----CONSTANTS---- //
// ***************** //

`include "constants.tf"

// ***************** //
// -------END------- //
// ***************** //


// ************************** //
// ----PHYSICAL QUANTITES---- //
// ************************** //

`include "air.tf"

// ************************** //
// -----------END------------ //
// ************************** //


// *********************** //
// ----TECHNOLOGY FILE---- //
// *********************** //

//`include "./tech/irst.tf"
//`include "./tech/poly.tf"
`include "./tech/irst_new.tf"
//`include "./tech/philips_04_06_2004.tf"

// *********************** //
// ----------END---------- //
// *********************** //
```

The first two inclusions are for the **"constants.tf"** and **"air.tf"** files which are located in the same subfolder as **"quantities.tf"** and which define some constants and the air characteristic values (e.g. viscosity and permittivity), respectively. If for instance we are interested in simulating a MEMS structures within a Nitrogen atmosphere instead of air, the values within **"air.tf"** are to be modified

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

or a new file (e.g. **"nitrogen.tf"**) containing the proper values has to be created within the current subfolder and then included in **"quantities.tf"** (with the line **" `include "nitrogen.tf" "**).

Concerning the technology file with materials information, four of them are declared within **"quantities.tf"** but just one of them is chosen (in this case "**irst_new.tf**"). Technology files are located in the following path:
"/users/OPUS/MEMS_MODELER_CONTAINER_VerilogA/qunatities/tech/"
and the content of **"irst_new.tf"** is following:

```
/////////////////////////////////  GOLD VALUES  ////////////////////////////////

rho= 0.005;             // Structural layer sheet resistance ohm/square.
E=98.5e9;               // Youngs modulus (Pascal).
dens=19300.0;           // density (kg/m^3).
Poi_nu=0.42;            // Poisson's ratio.
thox=100.0e-9;          // Oxide thickness above bottom plate.
erox=5.7;               // Oxide dielectric constant
rough_air_spacer=0;     // Extra air gap due to the oxide roughness.
K_touch=10.0G;          // Fictitious elastic parameter when collision occurs.
min_dist = 10.0e-6;     // Minimum distance between two hole on plate surface.
Stat_damp = 9.0e-2;     // Static damping coefficient.
Dyna_damp = 2.0e-2;     // Dynamic damping coefficient.

////////////////////////////////////////////////////////////////////////////////
```

The meaning of each of the just listed parameters is summarized in Table 4.

PARAMETER NAME	MEANING
rho	Structural Gold layer sheet resistance (Ohm/sq.).
E	Gold Young Modulus (Pa).
dens	Gold density (Kg/m^3).
Poi_nu	Gold Poisson's ratio.
thox	Oxide layer thickness onto the substrate (lower electrode) (m) .
erox	Oxide dielectric constant (F/m).
rough_air_spacer	Effective value of the lower electrode oxide roughness (m). **NOTE:** Defines the residual air gap due to the surface roughness when the pull-in is reached.
K_touch	Fictitious elastic constant defining the lower plane when pull-in occurs (N/m).
min_dist	Minimum distance between two adjacent holes (m). **NOTE:** It is not used in the beam model but refers to the rigid plate (see next pages).
Stat_damp	Static friction coefficient when collision occurs (no-dimension). **NOTE:** It is not used in the beam model but refers to the rigid plate (see next

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

	pages).
Dyna_damp	Dynamic friction coefficient when collision occurs (N*s/m). **NOTE:** It is not used in the beam model but refers to the rigid plate (see next pages).

Table 4: Summary of all the technology parameters within the "irst_new.tf" file.

If a new technology has to be defined it is possible either to modify the values of an existing file (like "**irst_new.tf**"), or to define a new file within the folder
"**/users/OPUS/MEMS_MODELER_CONTAINER_VerilogA/qunatities/tech/**"
and then include it in the **"quantities.tf"** header file (being the latter solution more straightforward).

NOTE

Every time a value is modified (in the constants or in the technology part) the model must be recompiled (see Figures 6 and 7) to make the change(s) effective.

Finally, in Figure 11 the 12 DOFs Cadence Composer Schematic is shown.

Figure 11: Cadence Composer Schematic of the 12 DOFs flexible beam. The two ends with 6 DOFs each are visible.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

5. The Rigid Plate Suspended Electromechanical Transducer

In this section the 6 DOFs rigid plate electrostatic transducer is going to be shown. The Cadence Composer Schematic is shown in Figure 12.

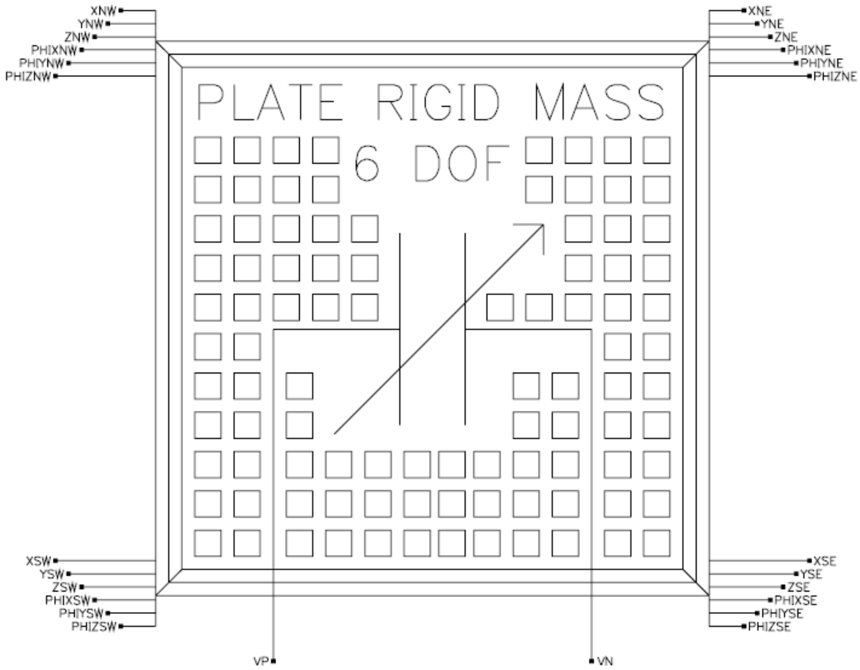

Figure 12: Cadence Composer Schematic of the 6 DOFs rigid plate suspended transducer. Four nodes are available for the interconnection of the device to the external world. These are named, starting from the top-right one as follows: North East (NE), South-East (SE), South-West (SW) and North-West (NW), respectively.

The way to use the rigid plate model is basically the same of the flexible beam shown in the previous section so it is possible referring to it when necessary.

Features Definition

The name of the subfolder containing the plate model is **"plate_Xdof_master"** in both the VerilogA and SpectreHDL implementations.

The list of all the possible features is contained in the files whose absolute path are: **"/users/OPUS/MEMS_MODELER_CONTAINER_VerilogA/plate_Xdof_master/main/main_plate.rgd"** and **"/users/OPUS/MEMS_MODELER_CONTAINER_SpectreHDL/plate_Xdof_master/main/main_plate.rgd"**.

Its content (for the VerilogA implementation) follows:

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

```
// ------------------------------------------------------ //

//`define Model_Reduction_To_4_Degrees_Of_Freedom

// ------------------------------------------------------ //

//`define Rotation_Matrix_Modified

`define Offset_Connectivity_Point

`define Contact_Effects

//`define In_Plane_Contact_Effects_Static

//`define In_Plane_Contact_Effects_Dynamic

// ------------------------------------------------------ //

`define Straight_Lines

`define Oxide_Electrical_Effects

`define Electrical_Effects_Capacitance

`define Electrical_Effects_Force

`define Boundary_Fringing_Capacitance

`define Boundary_Fringing_Electrostatic

`define Lateral_Fringing_Capacitance_Integral

`define Lateral_Fringing_Electrostatic_Integral

`define Manual_Holes_Placement

`define Holes_Capacitance

`define Holes_Electrostatic

`define Holes_Boundary_Fringing_Capacitance

`define Holes_Boundary_Fringing_Electrostatic

`define Holes_Lateral_Fringing_Capacitance_Integral

`define Holes_Lateral_Fringing_Electrostatic_Integral

//`define Electrostatic_Torques

// ------------------------------------------------------ //

`define Viscous_Damping_Effects

//`define Simplified_Viscous_Damping_Model

//`define Viscous_Damping_Torques_Model
```

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

```
//`define Simplified_Viscous_Damping_Torques_Model

//`define Discrete_Damping_Model

`define Mean_Free_Path_Model

// ------------------------------------------------------ //

//`define DC_Simulation_Model_Reduction

`define Torque_Nodes_Static_Damping_Inclusion

`define Torque_Nodes_Dynamic_Damping_Inclusion

`define Center_Of_Mass_Dynamic_Nodes_For_X

`define Center_Of_Mass_Dynamic_Nodes_For_Y

`define Center_Of_Mass_Dynamic_Nodes_For_Z

`define Center_Of_Mass_Dynamic_Nodes_For_Phi_X

`define Center_Of_Mass_Dynamic_Nodes_For_Phi_Y

`define Center_Of_Mass_Dynamic_Nodes_For_Phi_Z

// ------------------------------------------------------ //
```

In Table 5 the meaning of all the rigid plate features (reported above) is reported.

PARAMETER NAME	MEANING
Mechanical Model	#######################
Model_Reduction_To_4_Degrees_Of_Freedom	When set TRUE reduces the plate mechanical model to 4 Degrees of Freedom (DOFs) (three linear displacements and rotation allowed only around the vertical Z-axis). This means that the plate is always parallel to the substrate. When set FALSE the plate admits any position in space (6 DOFs, three linear displacements and rotations around the three axes X, Y, Z).
---------Plate Features---------	#######################
Rotation_Matrix_Modified	Defines a different analytical implementation for the rotation matrix compatible with large deformations [6]. **NOTE:** This feature is not tested and the variable should be left at FALSE value.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

Offset_Connectivity_Point	When set TRUE allows displacing the four interconnection points between the plate and the external world with respect to the four plate corners NE, SE, SW and NW (see Figure 12).
Contact_Effects	When set TRUE includes the presence of the substrate underneath the plate i.e. includes the collapse of the plate on the substrate. **NOTE:** If set FALSE none of the following features can be included.
In_Plane_Contact_Effects_Static	When TRUE includes the XY-in-plane static friction between the plate and the substrate when collision occurs. **NOTE:** The correct working of this feature has not been verified yet and might cause convergence problems. Moreover such an effect is usually not dominant in standard RF-MEMS switch topologies so this feature can be always set FALSE.
In_Plane_Contact_Effects_Dynamic	When TRUE includes the XY-in-plane dynamic (slithering) friction between the plate and the substrate when collision occurs. **NOTE:** The correct working of this feature has not been verified yet and might cause convergence problems. Moreover such an effect is usually not dominant in standard RF-MEMS switch topologies so this feature can be always set FALSE.
---------Electrostatic Effects---------	########################
Straight_Lines	When TRUE the electric field lines between the plate and the substrate are approximated to straight instead of curved lines. **NOTE:** When the plate mechanical model is reduced to 4 DOFs the field lines are always straight. When dealing with the 6 DOFs model it might happen very rarely that curved lines model causes convergence problems. In this case it can be set TRUE. The error increase in electrostatic force and capacitance calculation due to straight line approximation is rather small.
Oxide_Electrical_Effects	When TRUE counts in the electrical effects due to the oxide layer lying onto the lower substrate. The air gap and the oxide layer are treated as two series capacitances (see Figures 13 and 14).

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

Electrical_Effects_Capacitance	When set TRUE includes the calculation of capacitance between the plate and substrate.
Electrical_Effects_Force	When set TRUE includes the calculation of the attractive electrostatic force between the plate and substrate.
Boundary_Fringing_Capacitance	When TRUE the fringing capacitance due to the distortion of the field lines nearby the plate four edges is included in the capacitance calculation.
Boundary_Fringing_Electrostatic	When TRUE the fringing electrostatic force due to the distortion of the field lines nearby the plate four edges is included in the attractive force calculation.
Lateral_Fringing_Capacitance_Integral	When TRUE the fringing capacitance due to the field lines starting from the four plate boundary vertical sidewalls is included in the capacitance calculation. **NOTE:** When the plate is parallel to the substrate this contribution is equal to zero.
Lateral_Fringing_Electrostatic_Integral	When TRUE the fringing electrostatic force due to the field lines starting from the four plate boundary vertical sidewalls is included in the attractive force calculation. **NOTE:** When the plate is parallel to the substrate this contribution is equal to zero.
Manual_Holes_Placement	When TRUE the distance between the most peripheral holes edges and the plate boundaries can be defined by the user (see Figure 15). Otherwise the hole-edges clearance is automatically defined.
Holes_Capacitance	When TRUE includes in the model the presence of holes on the plate surface and calculates the effective capacitance value which also accounts for the holes. **NOTE:** When TRUE, holes presence is accounted also in the mechanical plate model (inertia) and in the viscous damping model.
Holes_Electrostatic	When TRUE includes in the model the presence of holes on the plate surface and calculates the effective electrostatic force value which also accounts for the holes. **NOTE:** When TRUE, the holes presence is accounted also in the mechanical plate model (inertia) and in the viscous damping model.
Holes_Boundary_Fringing_Capacitance	When TRUE the fringing capacitance due to the distortion of the field lines nearby the

	holes edges is included in the capacitance calculation.
Holes_Boundary_Fringing_Electrostatic	When TRUE the fringing electrostatic force due to the distortion of the field lines nearby holes edges is included in the attractive force calculation.
Holes_Lateral_Fringing_Capacitance_Integral	When TRUE the fringing capacitance due to the field lines starting from the holes vertical sidewalls is included in the capacitance calculation. **NOTE:** When the plate is parallel to the substrate this contribution is equal to zero.
Holes_Lateral_Fringing_Electrostatic_Integral	When TRUE the fringing electrostatic force due to the field lines starting from the holes vertical sidewalls is included in the attractive force calculation. **NOTE:** When the plate is parallel to the substrate this contribution is equal to zero.
Electrostatic_Torques	When TRUE the torque due to the attractive electrostatic force (occurring when the plate is not parallel to the substrate) is calculated. **NOTE:** The electrostatic torque contribution is usually very small and can be excluded from the model without significant accuracy loss.
---------Viscous Damping Effect---------	########################
Viscous_Damping_Effects	When TRUE includes the viscous damping effect in the rigid plate model. **NOTE:** If **"Holes_Capacitance"** or **"Holes_Electrostatic"** are set TRUE the viscous damping model accounts for the holes. Otherwise the plate is considered without openings on its surface.
Simplified_Viscous_Damping_Model	Considers a simplified mathematical implementation of the viscous damping model when there are **not** holes on plate surface. **NOTE:** When the plate is used without holes it is better to include the simplified model as it allows considerable simulation time saving and does not introduce significant accuracy loss.
Viscous_Damping_Torques_Model	When TRUE includes the calculation of the torque due to the viscous damping effect. **NOTE:** This contribution is not dominant so it can be reasonably neglected in the model definition.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

Simplified_Viscous_Damping_Torques_Model	Considers a simplified mathematical implementation of the viscous damping torque calculation. **NOTE:** See the note of previous parameter.
Discrete_Damping_Model	Considers a discrete implementation of the viscous damping effect when there are **not** holes on plate surface. **NOTE:** Since "**Simplified_Viscous_Damping_Model**" is a better choice when there are no holes, this feature can be always set FALSE.
Mean_Free_Path_Model	When TRUE includes the calculation of an effective fluid viscosity (according to the model proposed by Veijola [9]). **NOTE:** Since the so-called slip-flow becomes dominant when the air gap is very small (i.e. of the same order of magnitude of the mean free path) this feature must be included every time the pull-in is expected to be reached.
---------Convergence Aid---------	########################
DC_Simulation_Model_Reduction	When set TRUE cuts out of the compilation all the definitions of dynamic nodes (time derivatives). **NOTE: It** makes the model more robust against convergence problems but can be used only for static DC simulations as all the dynamics due to inertia and viscous damping are ignored.
Torque_Nodes_Static_Damping_Inclusion	Includes internal nodes for the static XY-in-plane friction and must be TRUE if "**In_Plane_Contact_Effects_Static**" is TRUE.
Torque_Nodes_Dynamic_Damping_Inclusion	Includes internal nodes for the dynamic XY-in-plane friction and must be TRUE if "**In_Plane_Contact_Effects_Dynamic**" is TRUE.
Center_Of_Mass_Dynamic_Nodes_For_X	When set FALSE does not include all the dynamic nodes (velocity and acceleration) for the X-linear displacement DOF. **NOTE:** May be used to increase convergence robustness but **cuts off** all the dynamic effects (inertia and viscous damping) related to the X-linear displacement DOF.
Center_Of_Mass_Dynamic_Nodes_For_Y	When set FALSE does not include all the dynamic nodes (velocity and acceleration) for the Y-linear displacement DOF. **NOTE:** May be used to increase convergence robustness

	but **<u>cuts off</u>** all the dynamic effects (inertia and viscous damping) related to the Y-linear displacement DOF.
Center_Of_Mass_Dynamic_Nodes_For_Z	When set FALSE does not include all the dynamic nodes (velocity and acceleration) for the Z-linear displacement DOF. **NOTE:** May be used to increase convergence robustness but **<u>cuts off</u>** all the dynamic effects (inertia and viscous damping) related to the Z-linear displacement DOF.
Center_Of_Mass_Dynamic_Nodes_For_Phi_X	When set FALSE does not include all the dynamic nodes (angular velocity and angular acceleration) around the X-axis. **NOTE:** May be used to increase convergence robustness but **<u>cuts off</u>** all the dynamic effects (inertia and viscous damping) related to the rotation around the X-axis.
Center_Of_Mass_Dynamic_Nodes_For_Phi_Y	When set FALSE does not include all the dynamic nodes (angular velocity and angular acceleration) around the Y-axis. **NOTE:** May be used to increase convergence robustness but **<u>cuts off</u>** all the dynamic effects (inertia and viscous damping) related to the rotation around the Y-axis.
Center_Of_Mass_Dynamic_Nodes_For_Phi_Z	When set FALSE does not include all the dynamic nodes (angular velocity and angular acceleration) around the Z-axis. **NOTE:** May be used to increase convergence robustness but **<u>cuts off</u>** all the dynamic effects (inertia and viscous damping) related to the rotation around the Z-axis.

Table 5: Description of all the possible features related to the rigid plate suspended electromechanical transducer model.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

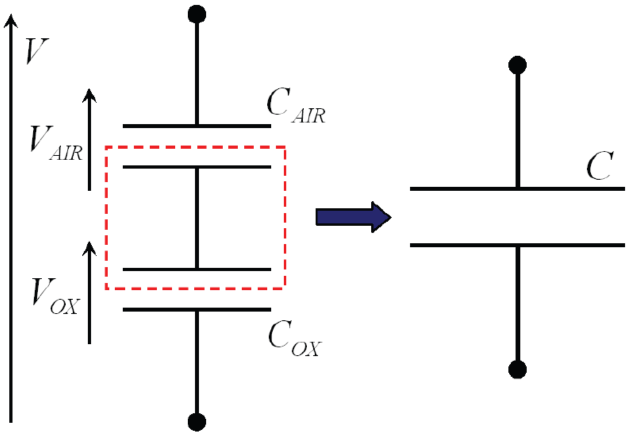

Figure 13: Air gap between the suspended plate and the surface plus the underlying oxide layer are modeled as two series capacitors.

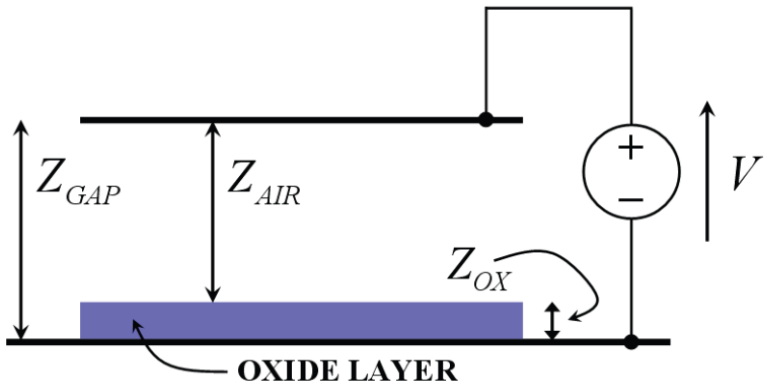

Figure 14: Schematic of the suspended rigid plate. It electrically behaves as a two parallel plate capacitor.

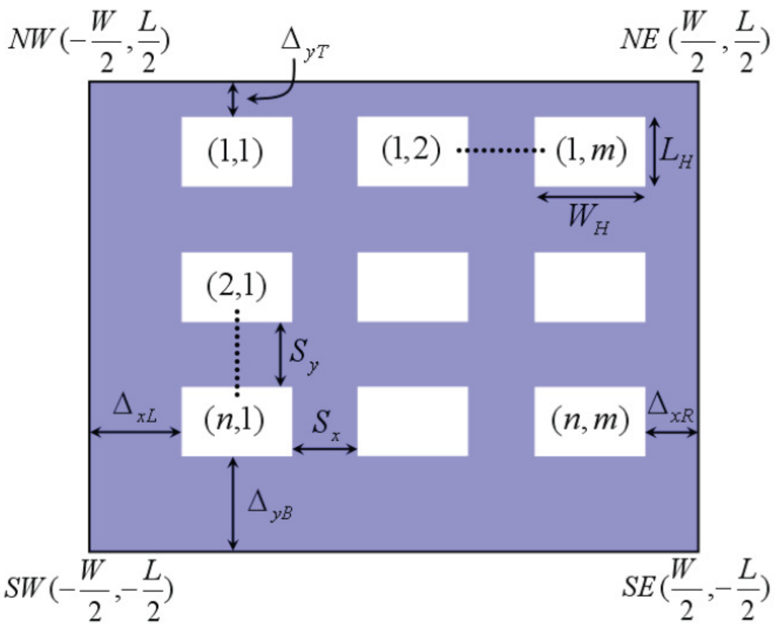

Figure 15: When the holes placement is set manual it is possible to define the four clearances addressed as Δ_{xL}, Δ_{xR}, Δ_{yB}, Δ_{yT}. This allows placing holes with different clearance for each plate edge.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

Figure 16: Rigid plate properties window in Cadence.

FONDAZIONE BRUNO KESSLER

<u>IMPORTANT NOTE</u>: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

In previous Figure 16 the Properties mask related to the rigid plate Cadence schematic is shown. The meaning of all the parameters is described in the following Table 6 and they correspond to the configuration of the "**main_plate.rgd**" file shown in previous pages.

PARAMETER	MEANING
w	Width of the rigid plate along the X-axis (see Figure 17). In this case **"w = 220 µm"** (see Figure 16).
L	Length of the rigid plate along the Y-axis (see Figure 17).
t	Thickness of the rigid plate along the Z-axis (see Figure 17).
angle_z	Plate initial rotation angle around the Z-axis (expressed in degrees) (see Figure 18).
gap	Vertical distance between the suspended plate and the underlying substrate. **NOTE:** The **"gap"** includes also the thickness of the insulating layer lying over the substrate.
fa	The parameter **"fringing arc"** defines the curvature of the fringing field lines nearby the plate edges (see Figure 19). It varies within the interval]0,1] and the larger it is, the more the field lines are curved (see Figure 20). **NOTE:** The **"fa"** parameter was *tuned* with FEM simulations and in can be kept equal to **0.25** [4, 5]**.**
fw	The parameter "**fringing width**" defines the area nearby the plate edges within which the fringing effect is supposed to be present (see Figure 21). **NOTE:** The **"fw"** parameter was *tuned* with FEM simulations and in can be kept equal to **100 nm** [4, 5].
sp_x_lft	Clearance (along the X-axis) between the left plate edge and the left edge of the first holes column (see Figure 15).
sp_x_rgt	Clearance (along the X-axis) between the right plate edge and the right edge of the last holes column (see Figure 15).
sp_y_bot	Clearance (along the Y-axis) between the bottom plate edge and the bottom edge of the lowest holes row (see Figure 15).
sp_y_top	Clearance (along the Y-axis) between the top plate edge and the top edge of the highest holes row (see Figure 15).
nhl_x	Number of holes (integer) along the X-axis.
nhl_y	Number of holes (integer) along the Y-axis.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

hl_x	Holes width along the X-axis (see Figure 15).
hl_y	Holes length along the Y-axis (see Figure 15).
fah	The parameter "**fringing arc holes**" defines the curvature of the fringing field lines nearby the holes edges. It varies within the interval]0,1] and the larger it is, the more curved the field lines are (refer to "**fa**"). **NOTE:** The "**fah**" parameter was *tuned* with FEM simulations and in can be kept equal to **0.25** [4, 5]**.**
fwh	The parameter **"fringing width holes"** defines the area nearby the holes edges within which the fringing effect is supposed to be present. (refer to "**fw**"). **NOTE:** The "**fwh**" parameter was *tuned* with FEM simulations and it can be kept equal to **100 nm** [4, 5].
fal	The parameter "**fringing arc lateral**" defines the curvature of the fringing field lines nearby the plate vertical sidewalls (see Figure 22). It varies within the interval]0,1] and the larger it is, the more curved the field lines are (see Figure 20). **NOTE:** The "**fal**" parameter was *tuned* with FEM simulations and in can be kept equal to **0.25** [4, 5]**.**
falh	The parameter **"fringing arc lateral holes"** defines the curvature of the fringing field lines nearby holes vertical sidewalls. It varies within the interval]0,1] and the larger it is, the more curved the field lines are (refer to **"fal"**). **NOTE:** The **"falh"** parameter was *tuned* with FEM simulations and in can be kept equal to **0.25** [4, 5]**.**
out_flag	Boolean flag. If set to "1" displays real time information about the electrostatic force and capacitance values during the simulation.
angle_x	Plate initial rotation angle around the X-axis (expressed in degrees) (see Figure 18).
angle_y	Plate initial rotation angle around the Y-axis (expressed in degrees) (see Figure 18).
fict_zero	Value considered as fictitious zero in order to avoid division by zero. **NOTE:** When nothing is specified in the mask it is set equal to 1e-6 by default. This value usually does not need to be modified.
offset_x_ne	Defines the displacement of the NE node from the top-right plate corner along the X-axis. The parameter is not available if

	"**Offset_Connectivity_Point**" is FALSE (see Table 5). **NOTE:** If this parameter has a non-zero value the following one must be zero.
offset_y_ne	Defines the displacement of the NE node from the top-right plate corner along the Y-axis. The parameter is not available if "**Offset_Connectivity_Point**" is FALSE (see Table 5). **NOTE:** If this parameter has a non-zero value the previous one must be zero.
offset_z_ne	Defines the displacement of the NE node from the top-right plate corner along the Z-axis. The parameter is not available if "**Offset_Connectivity_Point**" is FALSE (see Table 5).
offset_x_se	Defines the displacement of the SE node from the bottom-right plate corner along the X-axis. The parameter is not available if "**Offset_Connectivity_Point**" is FALSE (see Table 5). **NOTE:** If this parameter has a non-zero value the following one must be zero.
offset_y_se	Defines the displacement of the SE node from the bottom-right plate corner along the Y-axis. The parameter is not available if "**Offset_Connectivity_Point**" is FALSE (see Table 5). **NOTE:** If this parameter has a non-zero value the previous one must be zero.
offset_z_se	Defines the displacement of the SE node from the bottom-right plate corner along the Z-axis. The parameter is not available if "**Offset_Connectivity_Point**" is FALSE (see Table 5).
offset_x_sw	Defines the displacement of the SW node from the bottom-left plate corner along the X-axis. The parameter is not available if "**Offset_Connectivity_Point**" is FALSE (see Table 5). **NOTE:** If this parameter has a non-zero value the following one must be zero.
offset_y_sw	Defines the displacement of the SW node from the bottom-left plate corner along the Y-axis. The parameter is not available if "**Offset_Connectivity_Point**" is FALSE (see Table 5). **NOTE:** If this parameter has a non-zero value the previous one must be zero.
offset_z_sw	Defines the displacement of the SW node from the bottom-left plate corner along the Z-axis. The parameter is not available if

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

	"Offset_Connectivity_Point" is FALSE (see Table 5).
offset_x_nw	Defines the displacement of the NW node from the top-left plate corner along the X-axis. The parameter is not available if **"Offset_Connectivity_Point"** is FALSE (see Table 5). **NOTE:** If this parameter has a non-zero value the following one must be zero.
offset_y_nw	Defines the displacement of the NW node from the top-left plate corner along the Y-axis. The parameter is not available if **"Offset_Connectivity_Point"** is FALSE (see Table 5). **NOTE:** If this parameter has a non-zero value the previous one must be zero.
offset_z_nw	Defines the displacement of the NW node from the top-left plate corner along the Z-axis. The parameter is not available if **"Offset_Connectivity_Point"** is FALSE (see Table 5).

Table 6: Description of all the parameters in the plate schematic properties mask within Cadence.

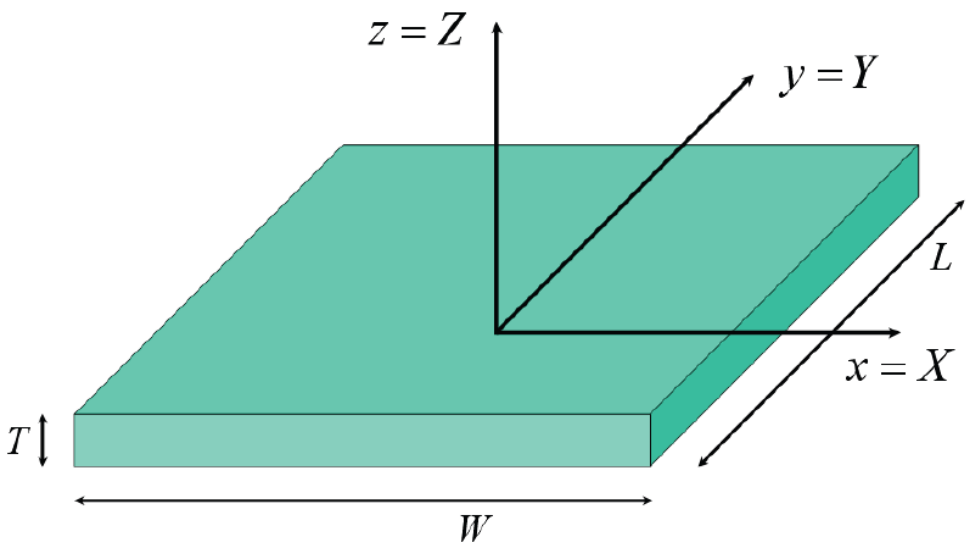

Figure 17: Schematic view of the 6 DOFs rigid plate suspended electrostatic transducer.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

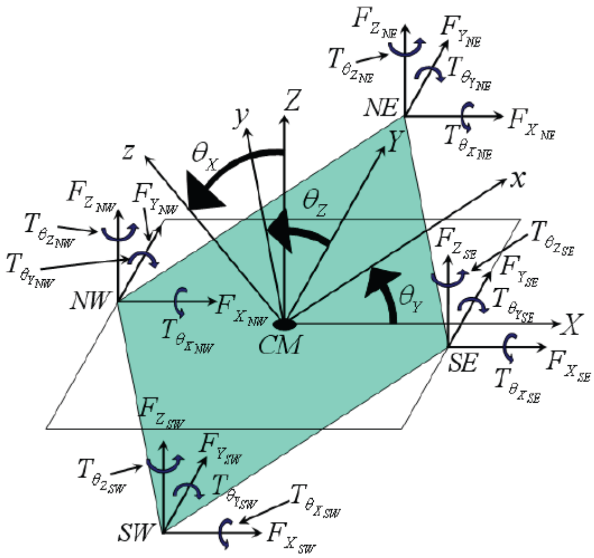

Figure 18: Schematic of the 6 DOFs rigid plate suspended electrostatic transducer (uneven position in space).

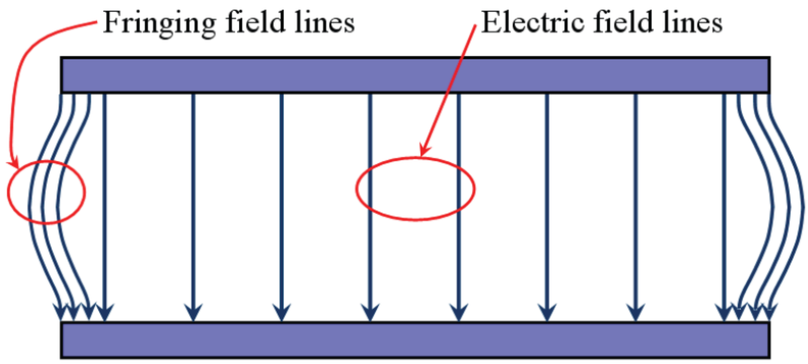

Figure 19: Fringing field lines nearby the plate edges.

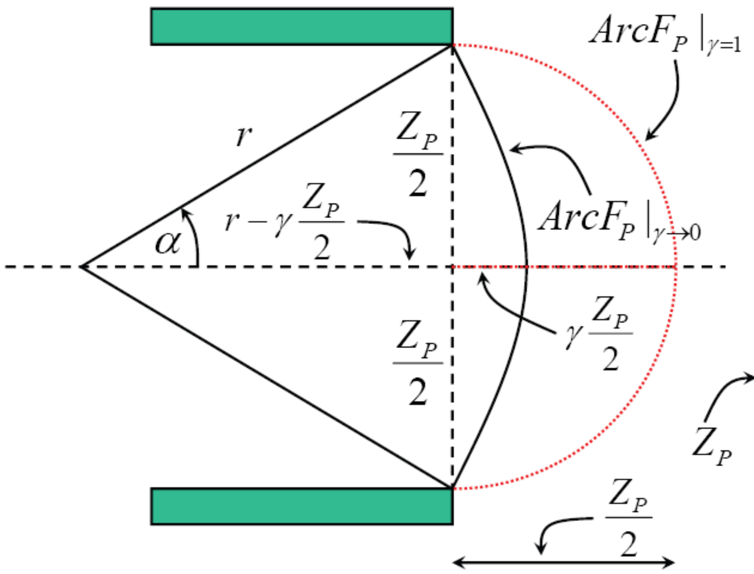

Figure 20: Definition of the parameter "fringing arc" (fa).

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

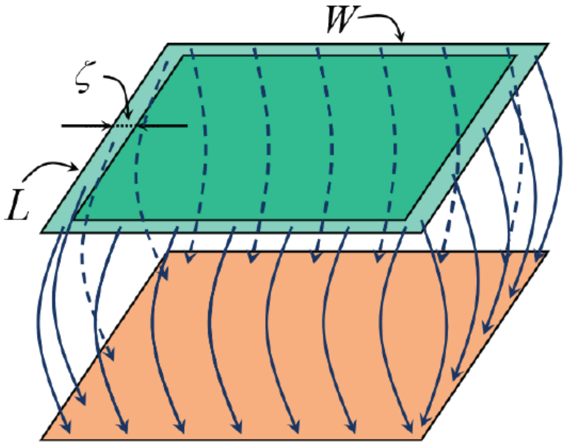

Figure 21: Definition of the "fringing width" (fw) parameter. The fringing effect is supposed to be confined within such region.

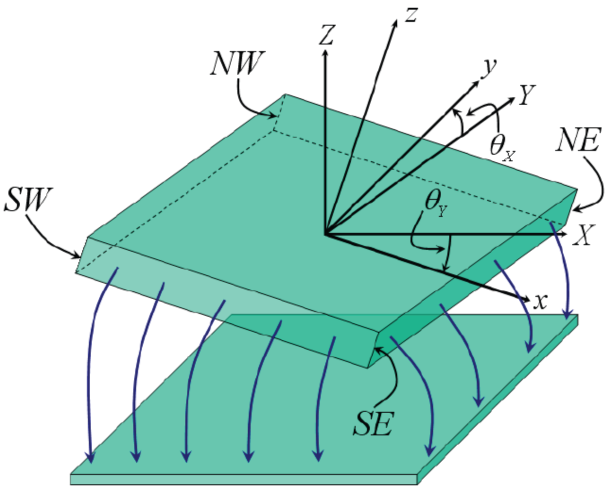

Figure 22: Schematic of the fringing field acting on plate vertical sidewalls when the plate assumes uneven position in space.

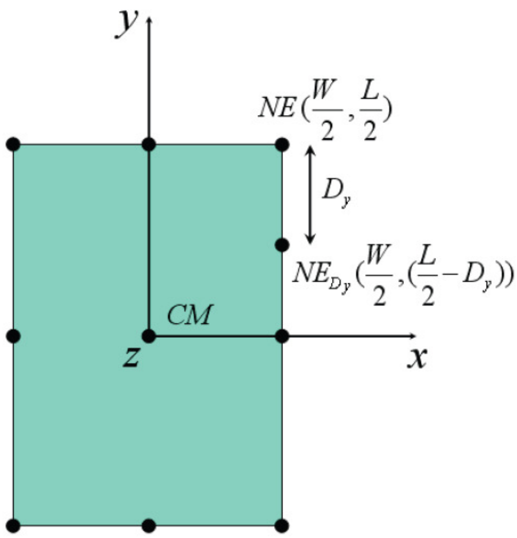

Figure 23: Example of displaced node with respect to the edge. In this case the North-East (NE) node is downshifted along the Y-axis direction.

FONDAZIONE BRUNO KESSLER

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

6. Complementary Components

In this section all the elementary components included in the library are described. These are necessary to achieve the complete description of RF-MEMS devices topologies. Complementary components can be divided in two categories: boundary conditions and stimulus sources and are described below.

Boundary Condition Components

Anchor Point

This device imposes a mechanical constraint to all the linear and angular DOFs and realizes an anchor point, indeed. Each of its nodes does not allow any displacement (linear or angular) in space to whatever device it is connected to. The 6 DOFs anchor element subfolder name within the libraries is **"anchor_6_degs"** and its Cadence schematic is shown in Figure 24.

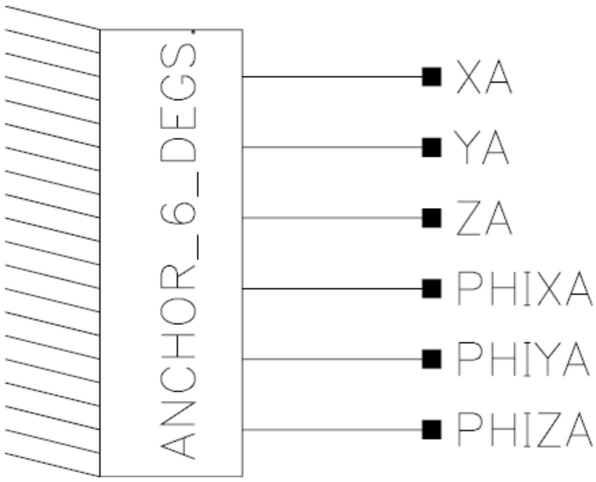

Figure 24: Cadence schematic of the 6 DOFs anchor point.

Anchor Point Minimum Resistance

When the anchor has to be connected to a rigid body (i.e. suspended rigid plate) it is like to short together two voltage generators in the electrical domain. This case cannot be managed by the Spectre simulator and an error occurs. To avoid this condition, an on purpose anchor element is available within the libraries. It is called "**anchor_6_degs_min_res**" and the Cadence schematic is reported in Figure 25. This element has a minimum resistance value defined within the model which prevents from the error condition mentioned above. The parameter "**r_min**" (which is the value of the minimum resistance) is accessible within the properties window within the schematic editor and if nothing is specified (i.e. the field is left blank) its default value is **1e-6 Ω**. If necessary its value can be modified.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

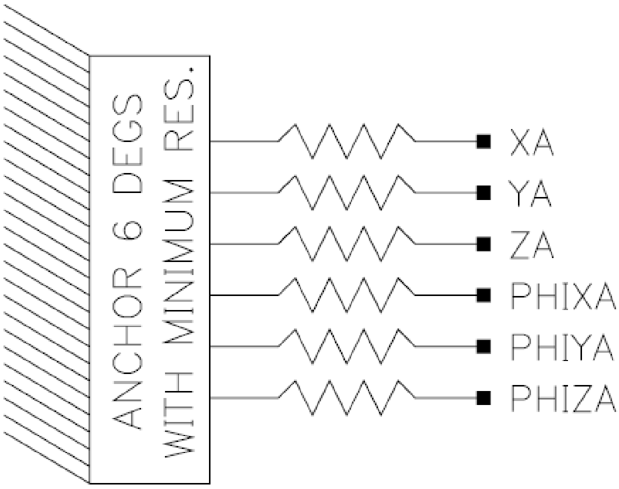

Figure 25: Cadence schematic of the 6 DOFs anchor point with minimum resistance.

Minimum Resistance Block

The same problem concerning the short condition stated by Spectre occurs when two rigid components (i.e. rigid plates) are connected together within the same schematic. To avoid this issue an element defining a minimum resistance between the input and output nodes is available within the library (only in the SpectreHDL version). Its subfolder name is **"min_res_l_a_6_pin"** and its Cadence schematic is shown in Figure 26. This element must be included in between two nodes of the rigid bodies to be connected together. The parameter "**r_min**" (which is the value of the minimum resistance) is accessible in the properties window within the schematic editor and if nothing is specified (i.e. the field is left blank) its default value is **1e-6 Ω**. If necessary its value can be modified. Depending on the number on nodes to be connected together the minimum resistance is available with different combinations others than the one of Figure 26. These are one, two or three linear node(s), respectively available as **"min_res_lin_1_pin"**, **"min_res_lin_2_pin"** and **"min_res_lin_3_pin"**, and one, two or three angular node(s), respectively available as **"min_res_ang_1_pin"**, **"min_res_ang_2_pin"** and **"min_res_ang_3_pin"**.

Figure 26: Cadence schematic of the 6 DOFs minimum resistance block.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

Unconnected Nodes Termination

Finally, it might happen that, in a certain design, some nodes remain floating (i.e. unconnected). This does not represent a real problem but Spectre generates a warning message and shorts those nodes to ground with a minimum conductance. To avoid this, a module defining an unconnected termination to which the floating nodes must be wired is available. Its name within both libraries is "**unc_l_a_6_pin**" and its Cadence schematic is reported in Figure 27.

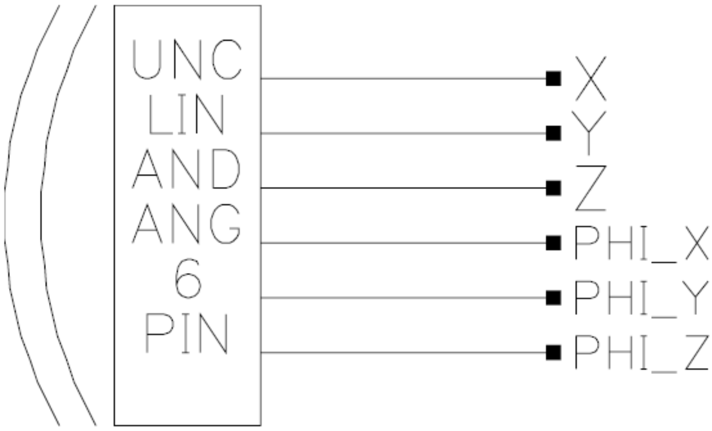

Figure 27: Cadence schematic for the 6 DOFs unconnected nodes termination.

Depending on the number on nodes to be terminated the floating element is available with different combinations others than the one of Figure 28. These are one, two or three linear node(s), respectively available as "**unc_lin_1_pin**", "**unc_lin_2_pin**" and "**unc_lin_3_pin**", and one, two or three angular node(s), respectively available as "**unc_ang_1_pin**", "**unc_ang_2_pin**" and "**unc_ang_3_pin**".

Stimulus Sources

Force Generator

This module generates a force to be applied to a certain MEMS structure. The name of the subfolder in both libraries is "**force_ang_6_full_degs**".

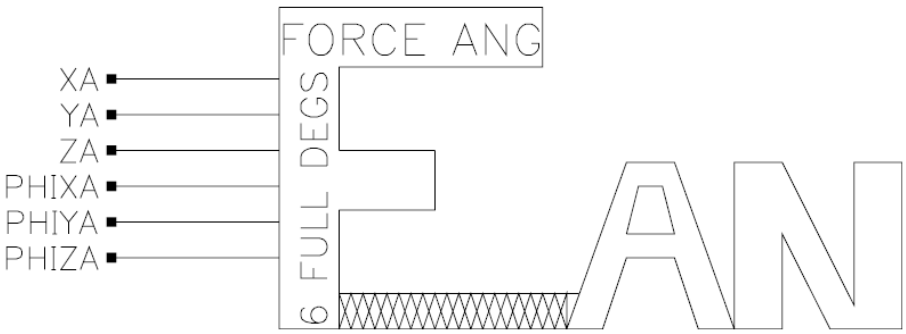

Figure 28: Cadence schematic for the 6 DOFs force source.

FONDAZIONE BRUNO KESSLER

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

Within the Cadence schematic properties window four parameters are available and these are described in Table 7.

PARAMETER	MEANING
angle_y	Defines the rotation (in degrees) of the force and torque (see next parameters) around the Y-axis.
angle_z	Defines the rotation (in degrees) of the force and torque (see next parameters) around the Z-axis.
torque_x	Defines the torque modulus (N*m) around the X-axis.
force_mod	Defines the force modulus (N) to be applied.

Table 7: Description of all the parameters within the "force_ang_6_full_degs" model.

Force Generator (AC Simulation)

This module generates a force to be applied to a certain MEMS structure for a small signal (AC) simulation within Spectre. Its name within both libraries is "**force_ac_5_degs**" and it allows only 5 DOFs (i.e. no torque is applied around the X-axis).

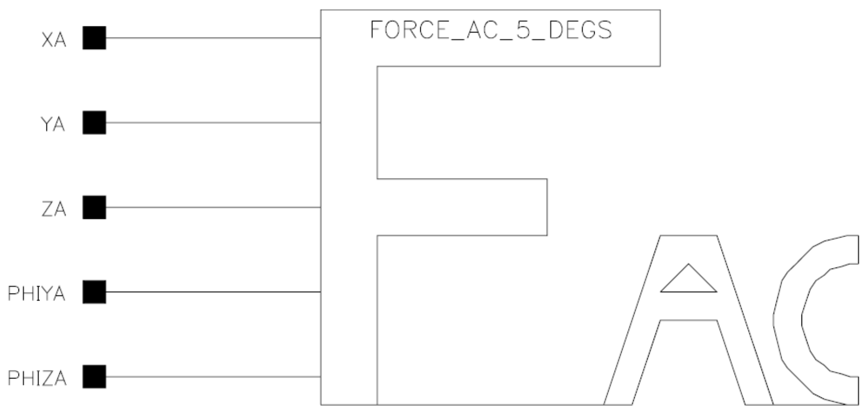

Figure 29: Cadence schematic for the 5 DOFs small signal AC force source.

<u>IMPORTANT NOTE</u>: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

Within the Cadence schematic properties window four parameters are available and these are described in Table 8.

PARAMETER	MEANING
forza	Defines the force modulus (N) to be applied.
phase	Defines the phase rotation to be applied to the force.
angle_y	Defines the rotation (in degrees) of the force around the Y-axis.
angle_z	Defines the rotation (in degrees) of the force around the Z-axis.

Table 8: Description of all the parameters within the "force_ang_6_full_degs" model.

<u>Force Generator (Pulse)</u>

This module generates a force pulse to be applied to a certain MEMS within Spectre. Its name within both libraries is "**force_ang_pulse_6_degs**". Its schematic is the same of Figure 28.

Within the Cadence schematic properties window seven parameters are available and these are described in Table 9.

PARAMETER	MEANING
angle_y	Defines the rotation (in degrees) of the force around the Y-axis.
angle_z	Defines the rotation (in degrees) of the force around the Z-axis.
t_delay	Defines the delay (seconds) of the pulse with respect to the zero-time point (see Figure 30).
t_rise	Defines the rising time (seconds) (see Figure 30).
t_on	Defines the duration of the high value of the pulse (seconds) (see Figure 30).
t_fall	Defines the fall time (seconds) (see Figure 30).
force_mod	Defines the force modulus (N) to be applied during the pulse "on" time. The pulse low force value is always zero.

Table 9: Description of all the parameters within the "force_ang_6_full_degs" model.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

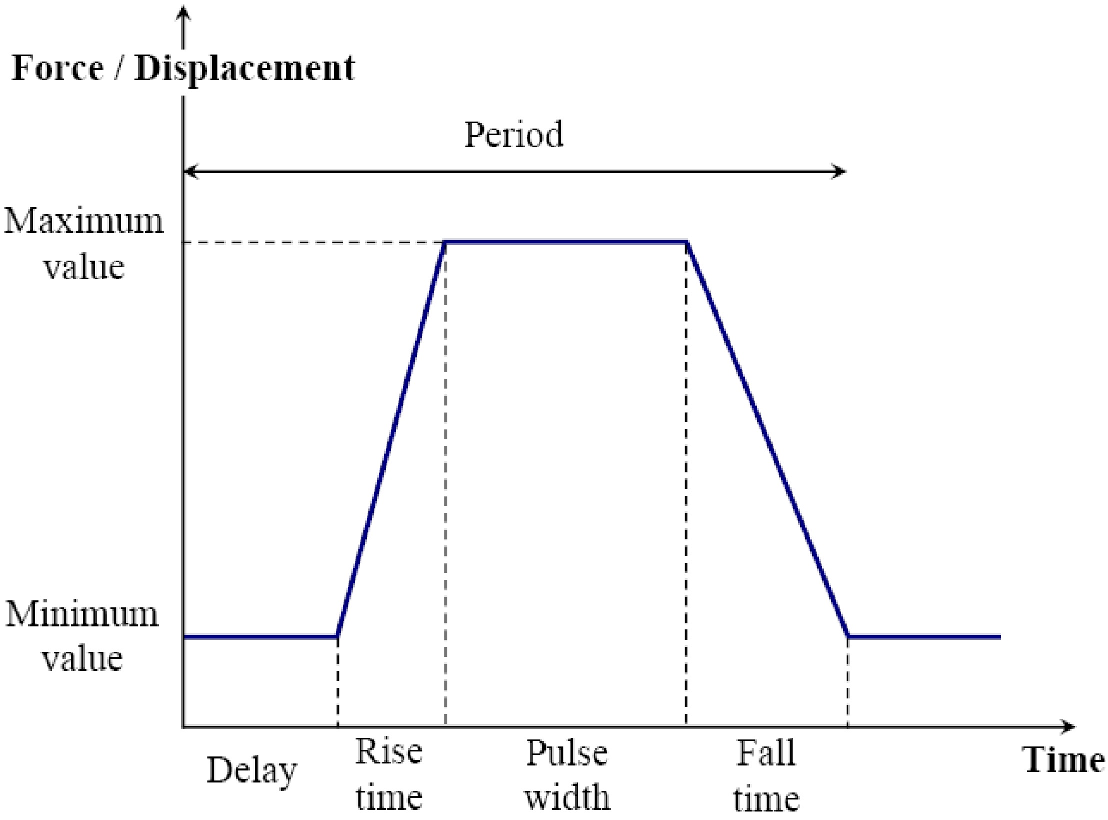

Figure 30: Pulse characteristic.

Displacememt Generator

This module generates a displacement to be applied to a certain MEMS structure.
The name of the subfolder (available only in the SpectreHDL implementation) is: **"displacements_ang_6_full_degs"**.

Figure 31: Cadence schematic for the 6 DOFs displacement source.

FONDAZIONE BRUNO KESSLER

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

Within the Cadence schematic properties window four parameters are available and these are described in Table 10.

PARAMETER	MEANING
displacement	Defines the displacement (m) to be applied to the MEMS structure.
rot_x	Defines the angular rotation (degrees) to be applied to the MEMS structure around the X-axis.
angle_y	Defines the rotation (in degrees) of the linear and angular displacement around the Y-axis
angle_z	Defines the rotation (in degrees) of the linear and angular displacement around the Z-axis

Table 10: Description of all the parameters within the "force_ang_6_full_degs" model.

IMPORTANT NOTE: Please report any problem, bug or malfunctioning of the library to the following email address: iannacci@fbk.eu.

7. References

[1]. "Affirma Spectre Circuit Simulator User Guide," Cadence Design Systems, Inc. Product Version 4.4.6, June, 2000.

[2]. "SpectreHDL Reference, Cadence Design Systems," Inc. Product Version 4.4.5, December, 1999.

[3]. "Affirma VerilogA Language Reference," Cadence Design Systems, Inc. Product Version 4.4.5, December, 1999.

[4]. J. Iannacci and R. Gaddi, "Mixed-Domain Simulation and Wafer-Level Packaging of RF-MEMS Devices", Lambert Academic Publishing – LAP,
Web: https://online.lap-publishing.com/index.php?&act=nav&nav=10039, ISBN: 978-3-8383-6421-6, Pages: 282, June 2010.

[5]. 1. J. Iannacci, R. Gaddi and A. Gnudi, "Experimental Validation of Mixed Electromechanical and Electromagnetic Modeling of RF-MEMS Devices Within a Standard IC Simulation Environment", Journal of Microelectromechanical Systems, IEEE, vol.19, no.3, pp.526-537, June 2010 ISSN: 1057-7157 doi: 10.1109/JMEMS.2010.2048417
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5466145&isnumber=5475379.

[6]. Qi Jing, "Modeling and for Design of Suspended MEMS," Ph. D. Dissertation in Electrical and Computer Engineering, Carnegie Mellon University Pittsburgh, Pennsylvania 15213, USA, Copyright 2003, Qi Jing.

[7]. J. S. Przemieniecki, Theory of Matrix Structural Analysis, McGraw-Hill, 1968.

[8]. Young-Ho Cho, A.P. Pisano and R.T. Howe, Viscous damping model for laterally oscillating microstructures, Journal of Microelectromechanical Systems, Volume 3, Issue 2, Pages 81-87, June 1994.

[9]. T. Veijola, H. Kuisma, and J. Lahdenpera, "Model for gas film damping in a silicon accelerometer, Proceedings of the International Conference on Solid-State Sensors Actuators," Volume 4, Pages 1097-1100, June 1997.