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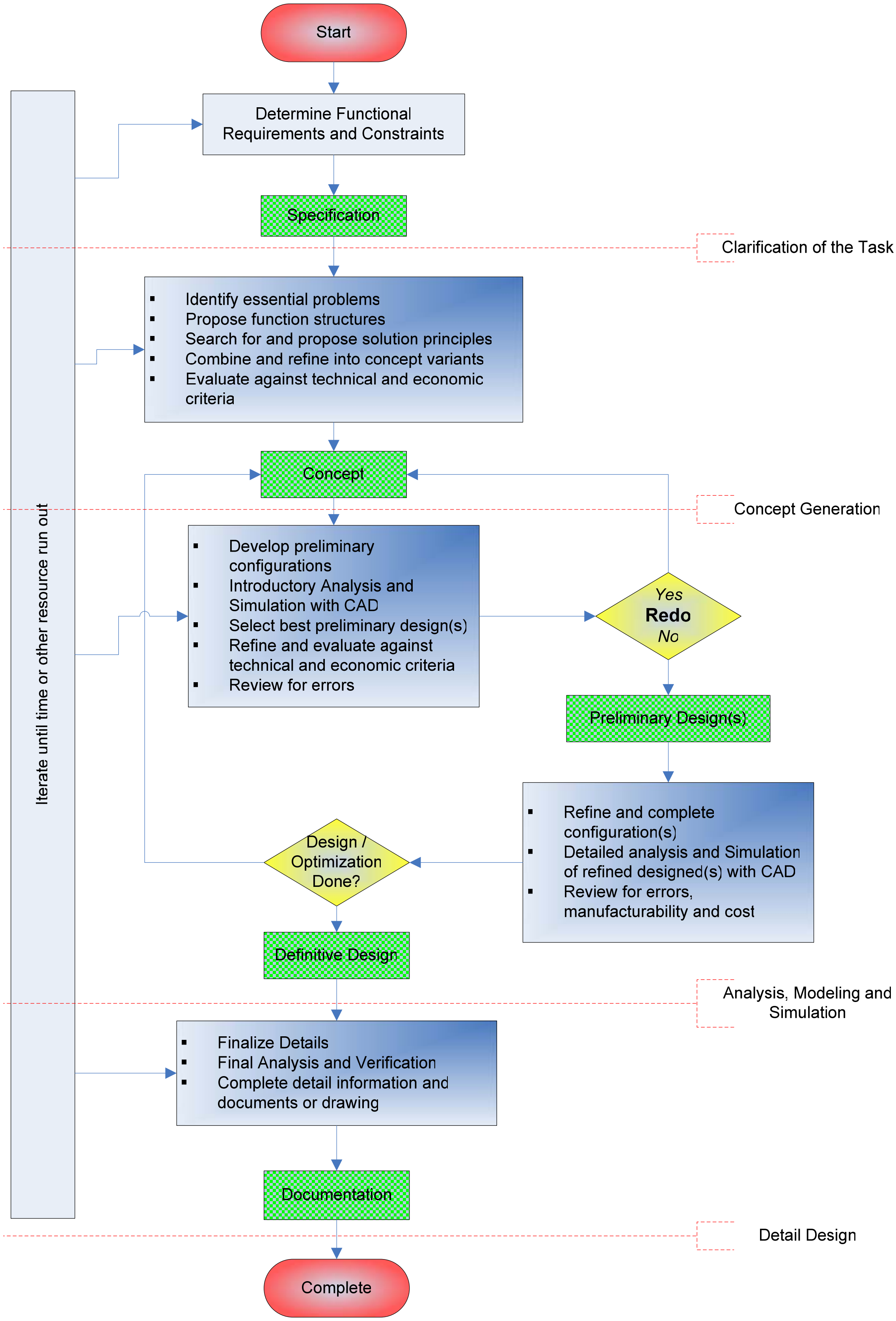
APPENDICES

Appendix A: Process flow



Appendix B: Mechanical Displacement Analyzer (MathCAD ver. 12)

Mechanical Displacement Analyzer:

Geometry Materials Properties Setting:

$Wp := 250 \cdot 10^{-6}$ $tp := 0.5 \cdot 10^{-6}$ $Ep := 210 \times 10^{9}$ $lp := 250 \cdot 10^{-6}$

$We := 270 \cdot 10^{-6}$ $te := 1 \cdot 10^{-6}$ $Ee := 160 \times 10^{9}$ $le := 100 \cdot 10^{-6}$

Applied voltage:

$V := 0.00001, 1 .. 10$

$d11 := 0$ $d12 := 0$ $d13 := 0$ $d14 := 0$ $d15 := -11.34$ $d16 := 0$

$d21 := 0$ $d22 := 0$ $d23 := 0$ $d24 := -11.34$ $d25 := 0$ $d26 := 0$

$d31 := -5.43$ $d32 := -5.43$ $d33 := 11.37$ $d34 := 0$ $d35 := 0$ $d36 := 0$

$$dij := \begin{pmatrix} d11 & d21 & d31 \\ d12 & d22 & d32 \\ d13 & d23 & d33 \\ d14 & d24 & d34 \\ d15 & d25 & d35 \\ d16 & d26 & d36 \end{pmatrix} \cdot 10^{-12}$$

Electrical Field:

$$E1(V) := \frac{V}{lp} \quad E2(V) := \frac{V}{Wp} \quad E3(V) := \frac{V}{tp} \quad E(V) := \begin{pmatrix} E1(V) \\ E2(V) \\ E3(V) \end{pmatrix}$$

$$S(V) := dij \cdot E(V)$$

Longitudinal Strain

$$s1(V) := d31 \cdot E3(V) \cdot 10^{-12}$$

Moment Inertial

$$ie := \frac{We \cdot te^{3}}{12} \qquad ip := \frac{Wp \cdot tp^{3}}{12}$$

Cross Sectional Area

$$Ae := We \cdot te \qquad Ap := Wp \cdot tp$$

$$Ae = 2.7 \times 10^{-10} \qquad Ap = 1.25 \times 10^{-10}$$

Radius of Curvature:

$$r(V) := \frac{4 \cdot (Ep \cdot ip + Ee \cdot ie) \cdot (Ap \cdot Ep + Ae \cdot Ee) + (Ap \cdot Ep \cdot Ae \cdot Ee) \cdot (tp + te)^{2}}{2 \cdot s1(V) \cdot (tp + te) \cdot (Ap \cdot Ep \cdot Ae \cdot Ee)}$$

Vertical Displacement of piezo segment

$$\delta p(V) := \frac{lp^{2} \cdot s1(V) \cdot (tp + te) \cdot Ae \cdot Ee \cdot Ap \cdot Ep}{4 \cdot (Ae \cdot Ee + Ap \cdot Ep)(Ep \cdot ip + Ee \cdot ie) + (te + tp)^{2} \cdot Ae \cdot Ee \cdot Ap \cdot Ep}$$

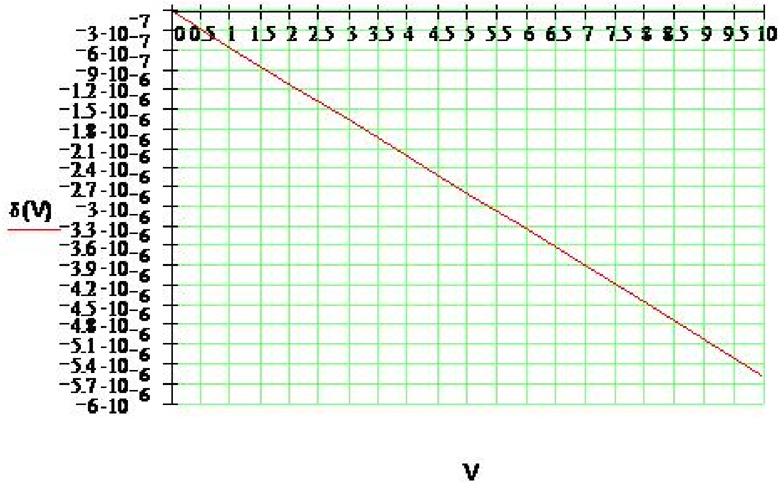
Angular Displacement at the end of the piezoelectric patch

$$\phi p(V) := \frac{lp}{r(V)}$$

Total maximum displacement of bimorph cantilever beam:

$$\delta(V) := \delta p(V) + le \cdot \sin(\phi p(V))$$

V =	δ(V) =
$1 \cdot 10^{-5}$	$-5.611?0^{-12}$
1	$-5.611?0^{-7}$
2	$-1.122?0^{-6}$
3	$-1.683?0^{-6}$
4	$-2.245?0^{-6}$
5	$-2.806?0^{-6}$
6	$-3.367?0^{-6}$
7	$-3.928?0^{-6}$
8	$-4.489?0^{-6}$
9	$-5.05?0^{-6}$
10	$-5.611?0^{-6}$

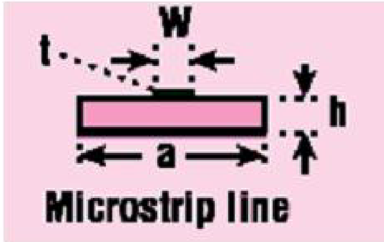


Appendix C: Materials properties

Ref	Material	Young's Modulus	Mass Density	Coupling factor	Poisson Ratio	R Curie Temp.	Dielectric Constant
		E (GPa)	ρ (kg/m^3)	k	v	(Ω-um) °C	εr
[4]	ZnO	210	5600	0.075		-	8.5
[4]	Quartz	107	2650	0.09		-	4.52
[4]	PZT-4	48-135	7500	0.6		365	1300-1475
[14]	Poly-Si	160	2330		0.23	23	11.7
[14]	SiO_2	69	2270		0.17	10^{11}-10^{14}	3.9
[14]	Si_3N_4	270	3170		0.24	1.00E+12	16
[14]	Au	80	19300		0.42	0.1	-
[14]	Al	70	2700		0.33	0.3	-

Appendix D: Microstrip Analyzer (MathCAD ver. 12)

Microstrip Calculator



Relative Permitivity: $\varepsilon r := 11.7$

Width od the line: $W := 74$

Height of the substrate: $H := 98$

$$\frac{W}{H} = 0.755$$

$$\varepsilon e := \begin{cases} \dfrac{\varepsilon r + 1}{2} + \dfrac{\varepsilon r - 1}{2} \cdot \left[1 + 12\left(\dfrac{H}{W}\right)\right]^{\frac{-1}{2}} & \text{if } \left(\dfrac{W}{H}\right) \geq 1 \\ \dfrac{\varepsilon r + 1}{2} + \dfrac{\varepsilon r - 1}{2} \cdot \left[\left[1 + 12\left(\dfrac{H}{W}\right)\right]^{\frac{-1}{2}} + 0.04\left[1 - \left(\dfrac{W}{H}\right)\right]^2\right] & \text{otherwise} \end{cases}$$

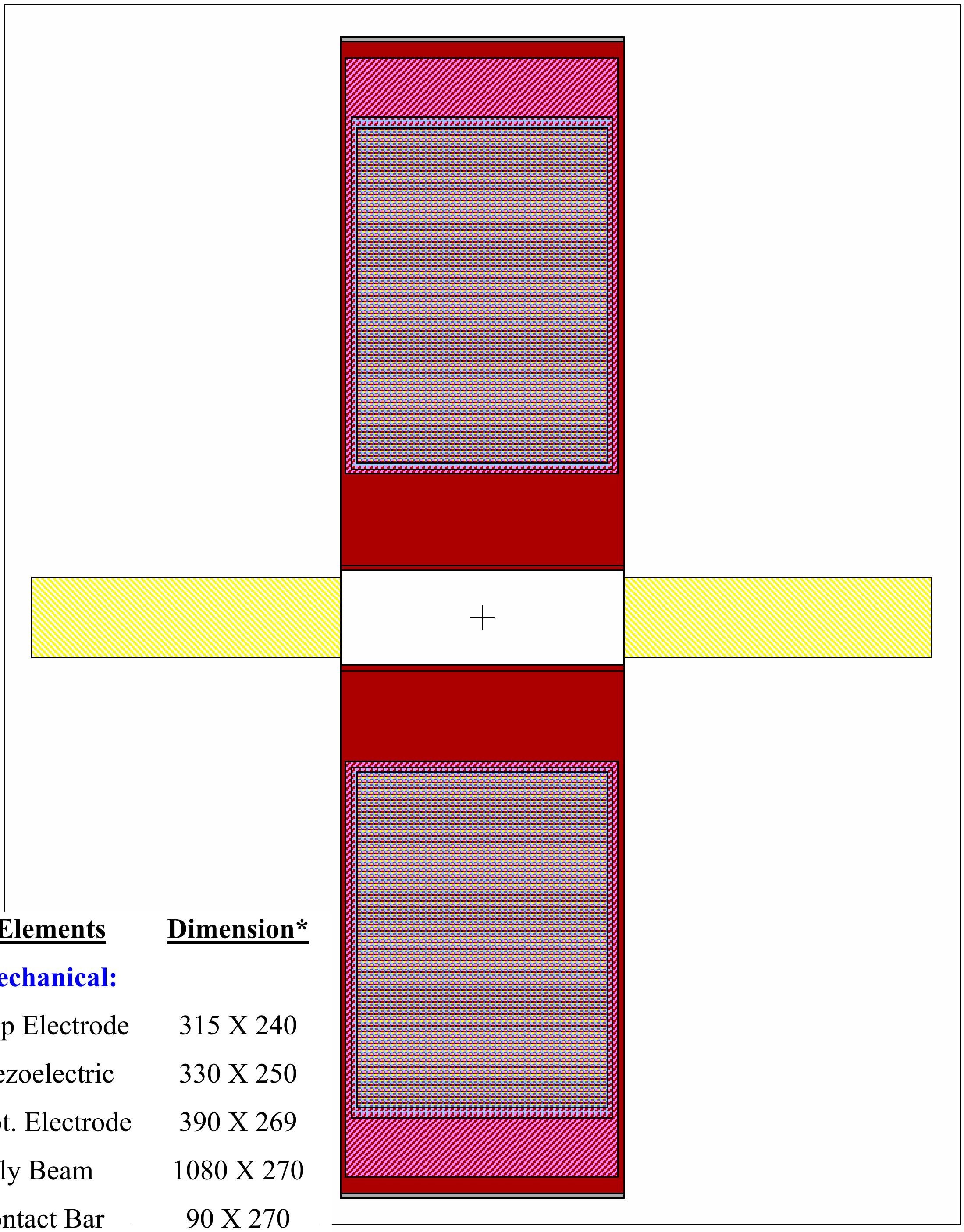
$$Zo := \begin{cases} \dfrac{120\pi}{\sqrt{\varepsilon e} \cdot \left(\dfrac{W}{H} + 1.393 + 2\ln\left(\dfrac{W}{H} + 1.444\right)\right)} & \text{if } \left(\dfrac{W}{H}\right) \geq 1 \\ \dfrac{60}{\sqrt{\varepsilon e}} \ln\left(8\dfrac{H}{W} + 0.25\dfrac{W}{H}\right) & \text{otherwise} \end{cases}$$

Effective Permitivity: $\varepsilon e = 7.665$

Line Impedance: $Zo = 51.537$

Note: Microwave calculator built with reference [21]

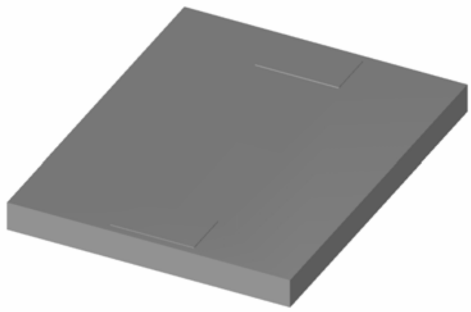
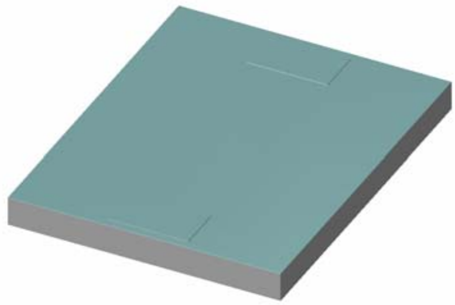
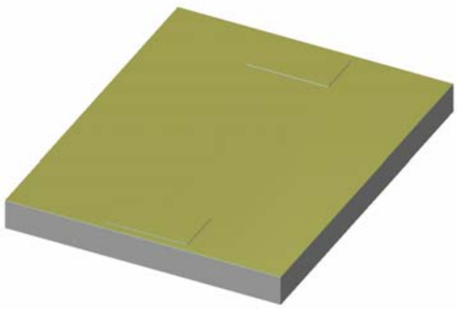
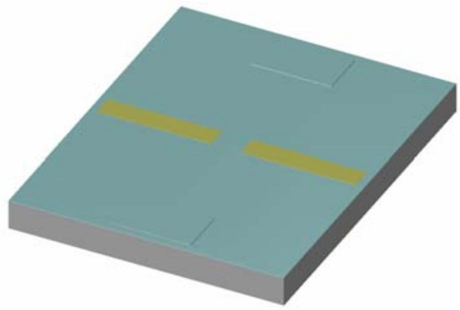
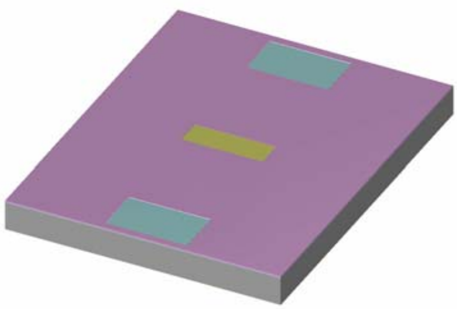
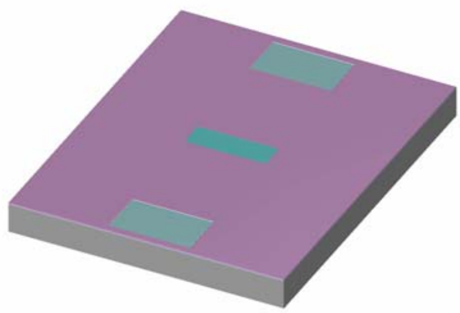
Appendix E: Full layout

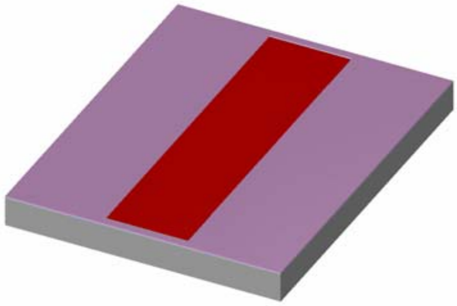
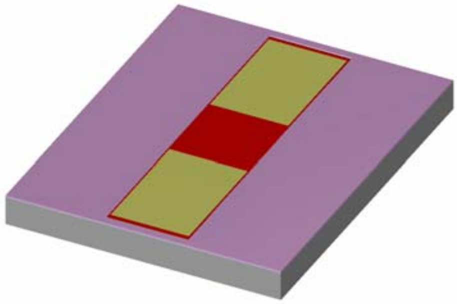
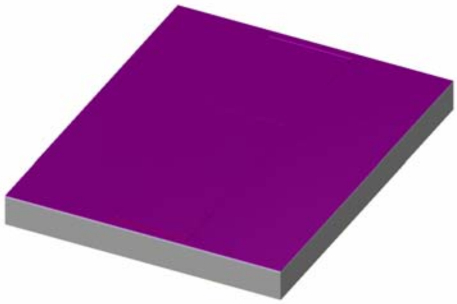
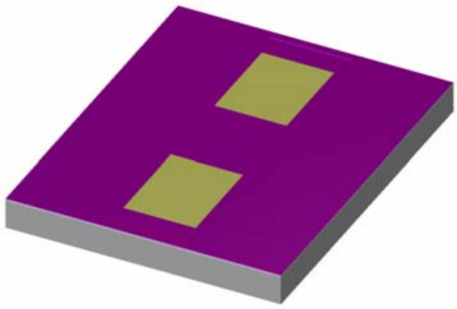
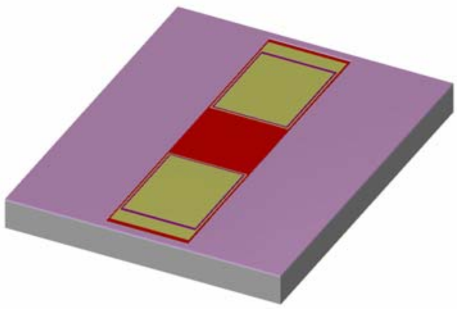
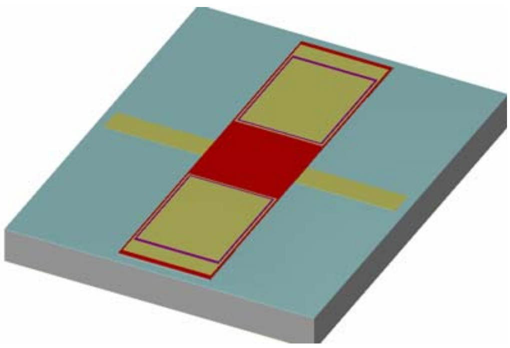


Elements	Dimension*
Mechanical:	
Top Electrode	315 X 240
Piezoelectric	330 X 250
Bot. Electrode	390 X 269
Poly Beam	1080 X 270
Contact Bar	90 X 270
Beam Anchor	155 X 270
Signal:	
Strip Line	74 X 380
Ground Plane	∞

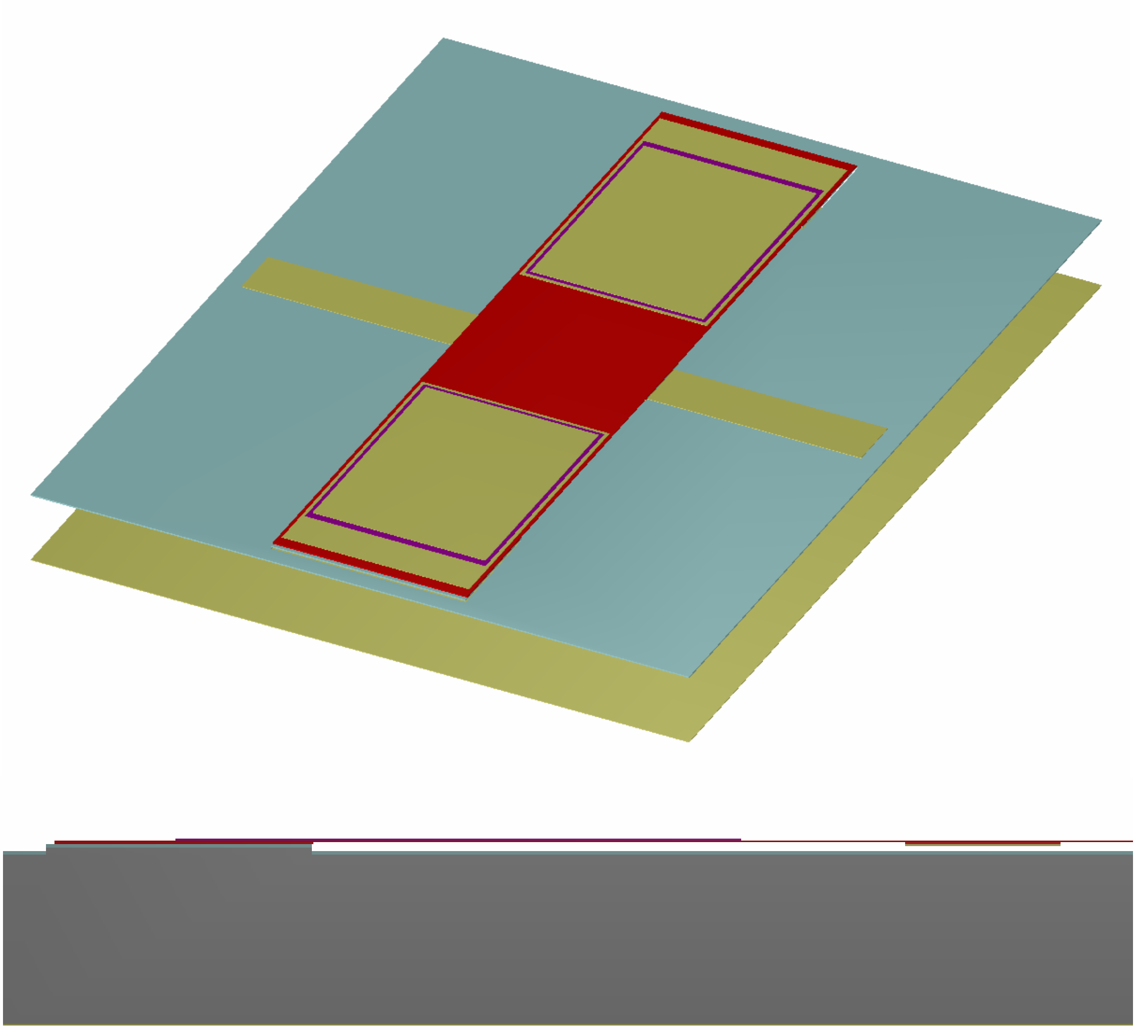
*All measurements in micrometer

Appendix F: 3D CAD Modeling process flow

1. 	2. 
3. 	4. 
5. 	6. 
7. 	8. 

9. 	**10.** 
11. 	**12.** 
13. 	**14.** 

Appendix G: Enlargement of 3D* full model and cross sectional



*(*Note: Substrate was hidden at 3D diagram)*

Appendix H: Currently available assembly types [27]

Samcef- Field Help - Analysis Data

Samcef Field | Desktop | Modeler | Analysis Data | Mesh | Solver | Result

Analysis Data

Contents

- **Using Analysis Data**
  - Assigning analysis data
- **The menus**
  - Data menu
  - Contextual menu
- **The tools**
- **The data tree**
- **Concepts**
- **OOFELIE specifics**
  - Vibro-acoustics
  - Piezoelectrics
  - Pyropiezoelectrics
  - Electrokinetic
  - Thermomechanics
  - Electromagnetics

Assembly types

This document describes the different types of assemblies that can be assigned to the model.

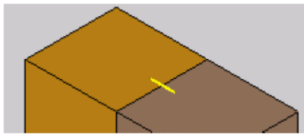
Assemblies are used to join two parts of the model. The two parts to the joined are termed "Support 1" and "Support2". Support 2 is considered to be mobile with respect to Support1, which is presumed to be fixed.

> In all cases two supports must be selected for an Assembly. The Order in which they are selected is important; the first selected item is Support 1 and the second Support 2.

- Fixed
- Mean
- Local Stiffness / Rotation Local Stiffness
- Gap
- Glue
- Connection Between Mesh Nodes
- Bearing
- Gear
- Hinge (Implicit Non Linear Analysis only)
- Prismatic (Implicit Non Linear Analysis only)
- Cylindric (Implicit Non Linear Analysis only)
- Spherical (Implicit Non Linear Analysis only)
- Screw (Implicit Non Linear Analysis only)
- Linear Motor (Implicit Non Linear Analysis only)
- Removable Link (Implicit Non Linear Analysis only)
- Universal Joint (Implicit Non Linear Analysis only)
- Slider (Implicit Non Linear Analysis only)
- Distance Sensor (Implicit Non Linear and Rotor Analysis only)
- Bushing
- Impact (Explicit Analysis only)
- Squeeze-Film Damper (Rotor Analysis only)
- Hydrodynamic-Bearing (Rotor Analysis only)

Fixed

A **Fixed** assembly joins the two parts rigidly together.



Note, even if the two supports are flexible, they will be made rigid.

This type of assembly can be applied to solids, faces, lines (edges and wires) and points.

No other parameters are required.

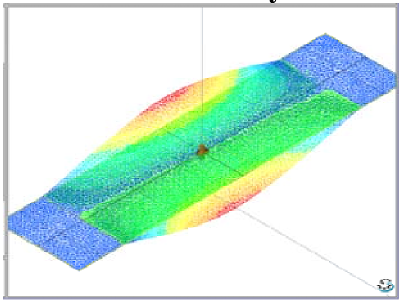
The [Apply] button will be available once the two supports have been selected.

A Fixed assembly is represented by a bar as shown in the figure alongside.

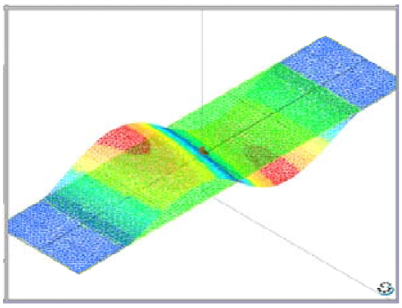
Remark:

For those highlighted are presenting in the software, and vice versus are currently absent and not available.

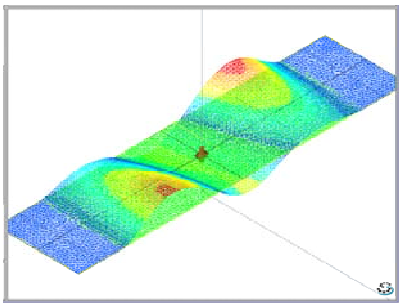
Appendix I: Modal analyses beam vibration characteristics



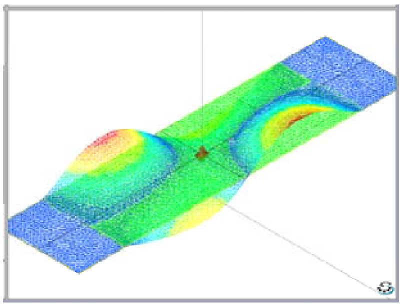
Mode [2]: 1.018181 MHz



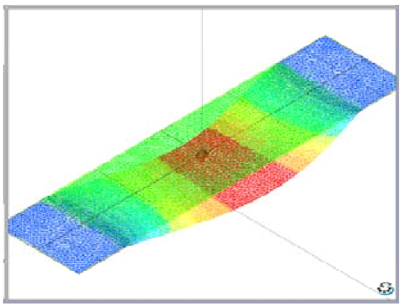
Mode [3]: 1.064199 MHz



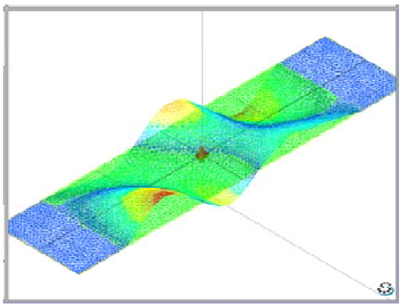
Mode [4]: 1.992676 MHz



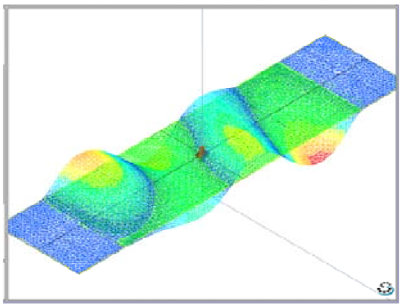
Mode [5]: 2.106546 MHz



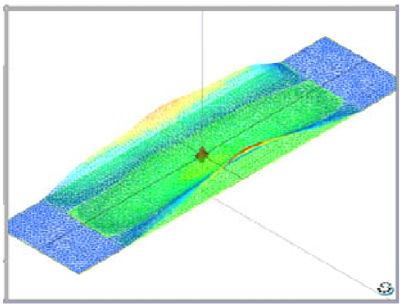
Mode [6]: 2.33448 MHz



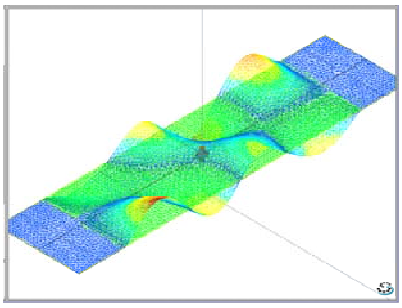
Mode [7]: 3.212142 MHz



Mode [8]: 3.415466 MHz



Mode [9]: 3.610447 MHz

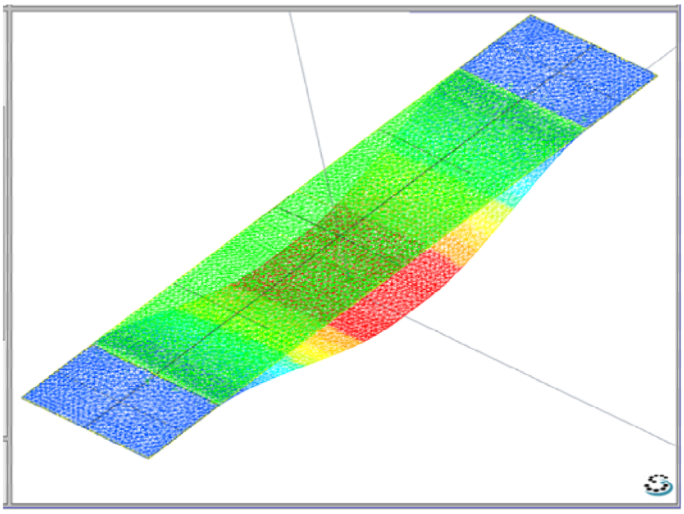


Mode [10]: 4.760311 MHz

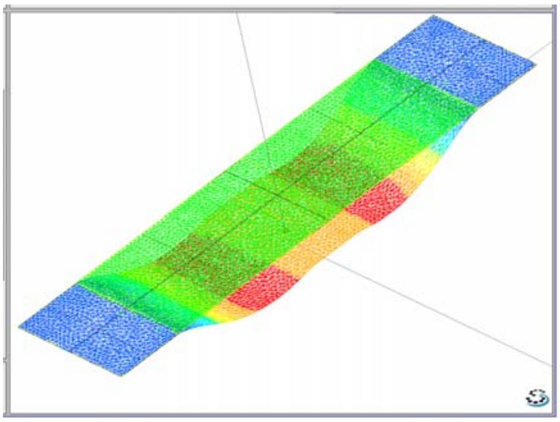
Appendix J: Harmonic response analysis-nodal displacement (DX.DY,DZ)

[Code 163]

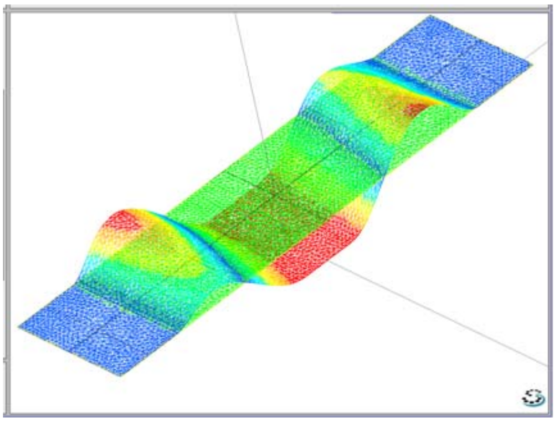
Frequency [kHz]	Node 2630 [1] (micron)	Node 5267 [1] (micron)	Node 808 [1] (micron)	Node 2361 [1] (micron)	Node 1641 [1] (micron)
100	0.9581	1.8042	2.0000	1.7009	1.0794
200	0.9691	1.8090	2.0000	1.7079	1.0904
300	0.9879	1.8171	2.0000	1.7198	1.1091
400	1.0151	1.8288	2.0000	1.7370	1.1362
500	1.0519	1.8444	2.0000	1.7599	1.1728
600	1.0998	1.8645	2.0000	1.7895	1.2202
700	1.1608	1.8900	2.0000	1.8269	1.2804
800	1.2382	1.9218	2.0000	1.8736	1.3564
900	1.3363	1.9617	2.0000	1.9320	1.4523
1000	1.4618	2.0118	2.0000	2.0053	1.5740
1100	1.6246	2.0758	2.0000	2.0987	1.7306
1200	1.8408	2.1594	2.0000	2.2200	1.9365
1300	2.1376	2.2722	2.0000	2.3824	2.2154
1400	2.5650	2.4319	2.0000	2.6095	2.6099
1500	3.2262	2.6750	2.0000	2.9481	3.2048
1600	4.3727	3.0901	2.0000	3.5065	4.1958
1700	6.8218	3.9658	2.0000	4.6027	6.1589
1800	15.5819	7.0688	2.0000	7.7574	11.8467
1900	-55.3767	-17.9486	2.0000	118.5870	212.4530
2000	-10.0333	-1.9380	2.0000	-5.9740	-13.0627
2100	-5.5481	-0.3391	2.0000	-2.2110	-6.2797
2200	-3.8550	0.2767	2.0000	-0.9952	-4.1098
2300	-2.9688	0.6099	2.0000	-0.3862	-3.0405
2400	-2.4257	0.8248	2.0000	-0.0140	-2.4021
2500	-2.0598	0.9812	2.0000	0.2425	-1.9749
2600	-1.7972	1.1079	2.0000	0.4353	-1.6639
2700	-1.5986	1.2281	2.0000	0.5917	-1.4169
2800	-1.4347	1.4136	2.0000	0.7327	-1.1836
2900	-1.3900	0.8854	2.0000	0.9556	-0.6159
3000	-1.2540	1.2704	2.0000	0.8315	-1.3337
3100	-1.1702	1.3735	2.0000	0.9658	-1.0763
3200	-1.1032	1.4494	2.0000	1.0646	-0.9513
3300	-1.0478	1.5174	2.0000	1.1563	-0.8581
3400	-1.0017	1.5830	2.0000	1.2467	-0.7799
3500	-0.9630	1.6490	2.0000	1.3389	-0.7104
3600	-0.9304	1.7173	2.0000	1.4354	-0.6462
3700	-0.9031	1.7894	2.0000	1.5384	-0.5848
3800	-0.8804	1.8671	2.0000	1.6507	-0.5239
3900	-0.8617	1.9522	2.0000	1.7751	-0.4616
4000	-0.8466	2.0469	2.0000	1.9157	-0.3956
4100	-0.8348	2.1540	2.0000	2.0775	-0.3230
4200	-0.8261	2.2770	2.0000	2.2675	-0.2403
4300	-0.8205	2.4210	2.0000	2.4957	-0.1422
4400	-0.8178	2.5928	2.0000	2.7767	-0.0212
4500	-0.8180	2.8028	2.0000	3.1338	0.1346
4600	-0.8214	3.0667	2.0000	3.6052	0.3455
4700	-0.8280	3.4101	2.0000	4.2595	0.6482
4800	-0.8380	3.8774	2.0000	5.2328	1.1167
4900	-0.8511	4.5537	2.0000	6.8394	1.9250
5000	-0.8660	5.6240	2.0000	10.0034	3.5907



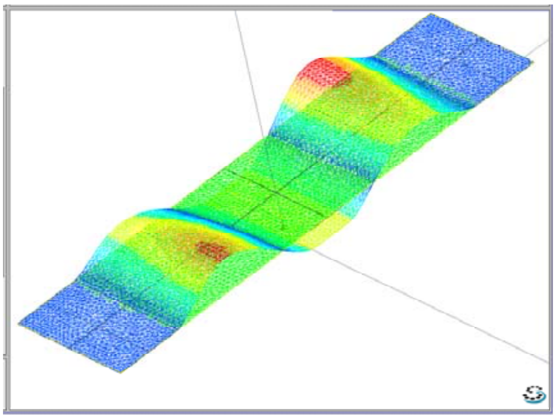
Frequency: 300 kHz



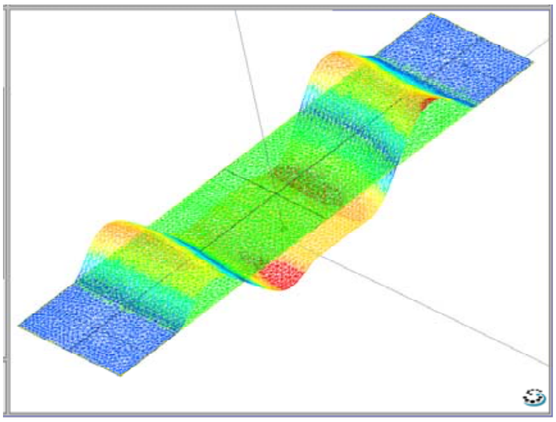
Frequency: 1300 kHz



Frequency: 3300 kHz



Frequency: 2300 kHz



Frequency: 4300 kHz

Appendix K: Transient response-nodal displacements (DX,DY,DZ) [Code 163]

Time [s]	Max Value	Min Value	Node 808 [1]	Node 3037 [1]	Node 3245 [1]	Node 3231 [1]	Node 2749 [1]	Node 3094 [1]
0	0	0	0	0	0	0	0	0
0.01	0	0	0	0	0	0	0	0
0.02	0	0	0	0	0	0	0	0
0.03	0	0	0	0	0	0	0	0
0.04	0	0	0	0	0	0	0	0
0.05	0	0	0	0	0	0	0	0
0.06	0	0	0	0	0	0	0	0
0.07	0	0	0	0	0	0	0	0
0.08	0	0	0	0	0	0	0	0
0.09	0	0	0	0	0	0	0	0
0.1	2.000685	-8.99E-04	2	1.992253	1.663386	1.246465	0.6229	0.093292
0.11	2.000574	-9.99E-04	2	1.993475	1.700374	1.302972	0.672413	0.103539
0.12	2.00075	-8.54E-04	2	1.991535	1.643157	1.217506	0.599644	0.088791
0.13	2.000629	-9.24E-04	2	1.99286	1.679087	1.267082	0.637332	0.095747
0.14	2.000681	-9.31E-04	2	1.9923	1.667904	1.257226	0.636417	0.09668
0.15	2.000669	-8.91E-04	2	1.99243	1.666299	1.247992	0.621252	0.092531
0.16	0.05387	-9.48E-05	0	9.77E-04	0.031323	0.049842	0.045588	0.009691
0.17	8.39E-05	-0.04487	0	-9.25E-04	-0.02779	-0.04192	-0.03589	-0.00727
0.18	0.01762	-4.38E-05	0	4.79E-04	0.012418	0.016121	0.010815	0.001726
0.19	0.006706	-0.00227	0	-1.33E-04	-0.00122	0.001815	0.005688	0.001793
0.2	1.16E-04	-0.0103	0	9.47E-07	-0.00246	-0.0069	-0.00943	-0.00245
0.21	0.006675	-5.66E-05	0	-1.99E-06	0.001643	0.004553	0.006066	0.001548
0.22	4.19E-04	-0.002	0	3.47E-05	8.44E-05	-9.19E-04	-0.00175	-4.81E-04
0.23	4.42E-06	-0.00131	0	-4.81E-05	-9.66E-04	-0.00104	-6.37E-04	-1.13E-04
0.24	0.001425	-3.48E-06	0	3.84E-05	9.02E-04	0.001216	0.001059	2.38E-04
0.25	1.84E-06	-8.08E-04	0	-2.03E-05	-4.45E-04	-6.02E-04	-5.73E-04	-1.41E-04
0.26	1.63E-04	-6.07E-07	0	6.03E-06	5.69E-05	2.86E-05	5.63E-05	2.80E-05
0.27	2.36E-04	-3.42E-06	0	5.76E-07	1.09E-04	2.10E-04	1.66E-04	2.35E-05
0.28	1.02E-06	-2.16E-04	0	-1.63E-06	-1.08E-04	-1.90E-04	-1.49E-04	-2.28E-05
0.29	1.09E-04	-1.15E-06	0	5.65E-07	4.98E-05	8.30E-05	5.17E-05	4.21E-06
0.3	2.48E-05	-1.96E-05	0	4.16E-07	-3.47E-06	-2.51E-06	1.89E-05	9.01E-06
0.31	1.10E-07	-3.83E-05	0	-6.83E-07	-1.29E-05	-2.48E-05	-3.83E-05	-1.14E-05
0.32	2.79E-05	-7.74E-08	0	4.74E-07	9.73E-06	1.85E-05	2.64E-05	7.50E-06
0.33	3.38E-08	-1.15E-05	0	-1.77E-07	-1.90E-06	-4.27E-06	-8.63E-06	-2.71E-06
0.34	6.31E-07	-4.91E-06	0	7.56E-10	-2.70E-06	-4.17E-06	-1.98E-06	-1.23E-07
0.35	5.52E-06	-2.84E-08	0	4.07E-08	3.18E-06	5.31E-06	4.37E-06	8.94E-07
0.36	3.02E-08	-3.58E-06	0	-1.52E-08	-1.67E-06	-2.89E-06	-2.61E-06	-6.04E-07
0.37	1.12E-06	-8.44E-08	0	-1.60E-08	1.75E-07	4.10E-07	4.26E-07	1.51E-07
0.38	8.12E-07	-6.03E-08	0	2.78E-08	5.01E-07	7.44E-07	6.23E-07	8.13E-08
0.39	2.08E-09	-8.18E-07	0	-2.28E-08	-5.03E-07	-7.71E-07	-6.40E-07	-9.47E-08
0.4	4.88E-07	-1.12E-09	0	1.23E-08	2.50E-07	3.67E-07	2.63E-07	2.27E-08
0.41	8.67E-08	-1.21E-07	0	-4.19E-09	-3.73E-08	-2.77E-08	4.31E-08	3.46E-08
0.42	6.47E-09	-1.58E-07	0	4.58E-10	-4.82E-08	-1.01E-07	-1.45E-07	-4.85E-08
0.43	1.15E-07	-1.66E-09	0	2.05E-10	4.44E-08	8.44E-08	1.09E-07	3.41E-08
0.44	1.41E-09	-5.46E-08	0	2.15E-10	-1.37E-08	-2.61E-08	-3.86E-08	-1.41E-08
0.45	8.91E-09	-1.72E-08	0	-5.44E-10	-7.14E-09	-1.25E-08	-6.84E-09	1.39E-09
0.46	2.65E-08	-4.63E-11	0	5.07E-10	1.12E-08	2.07E-08	1.88E-08	2.77E-09
0.47	2.57E-11	-1.94E-08	0	-2.77E-10	-6.22E-09	-1.24E-08	-1.23E-08	-2.11E-09
0.48	8.63E-09	-1.28E-11	0	6.49E-11	4.52E-10	2.37E-09	3.01E-09	4.25E-10
0.49	2.95E-09	-7.80E-10	0	4.00E-11	2.34E-09	2.75E-09	1.98E-09	5.10E-10
0.5	5.79E-12	-3.45E-09	0	-5.39E-11	-2.38E-09	-3.18E-09	-2.54E-09	-5.62E-10