FIRST-PASS SYSTEM SUCCESS

APPLICATION WORKSHOPS FOR HIGH-PERFORMANCE ELECTRONIC DESIGN

"Compact high efficiency TFLM motor for reciprocating compressor applications"

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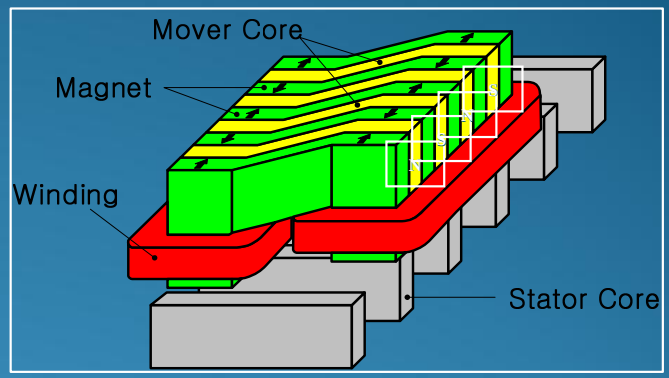
Korea Electrotehnology Research institute

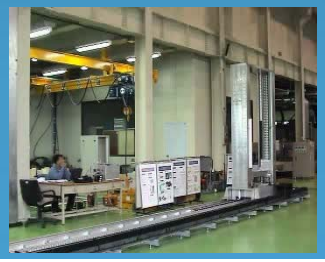
KERI Transversal Flux Machine Research

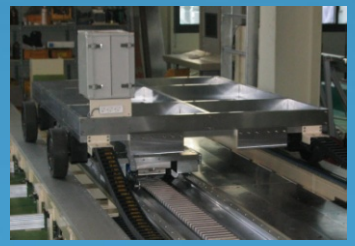
Development of **T**ransverse **F**lux **L**inear and **R**otating machine applications with high power density and high efficiency:

1.Transportation systems with TFLM;
2. Single and three phase TFRM for domestic applications;
3. Reciprocating compressor with short stroke TFLM;



- 1.Transportation systems with TFLM :
  - 300N TFLM commercialized for conveyer system
  - 1km long Overhead shuttle





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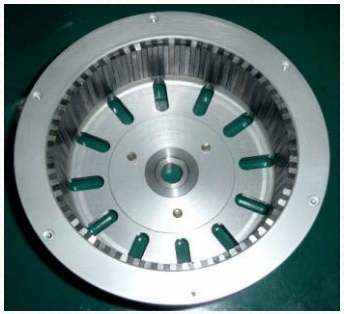
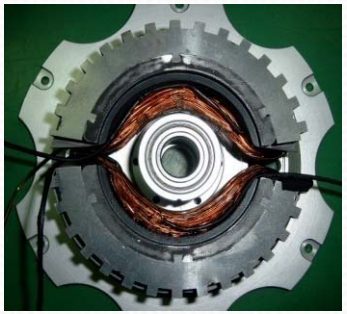
Single and three phase TFRM for domestic applications TFRM

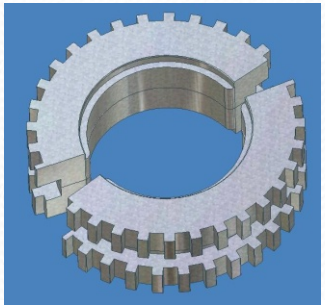




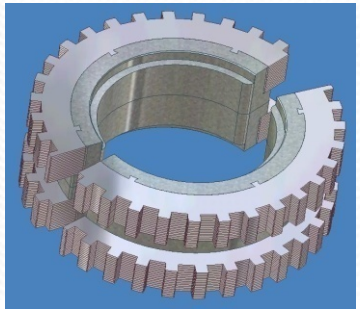
2Ph. TFM
In plane

2Ph. TFM
Axial arrangement

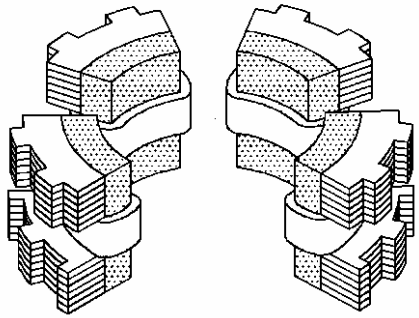
Type			
PM	LG (BLAC)	KERI (2Ph. In plane)	KERI (2Ph. Stack)
Out Dia.	301mm	196mm	196mm
Height	51.5mm	70mm	70mm
Volume	3665cm^3 (100%)	2112cm^3 (58%)	2112cm^3 (58%)
Eff. @ 300 rpm	80%	82%	89%



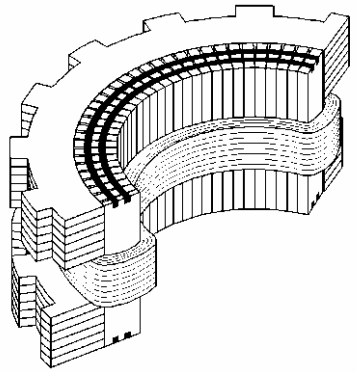
SMC core



SMC + Lamination

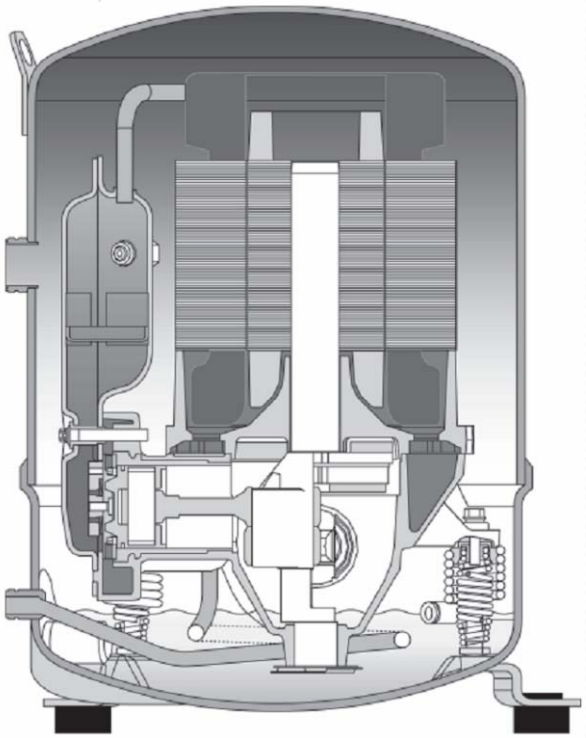


Multi-phase

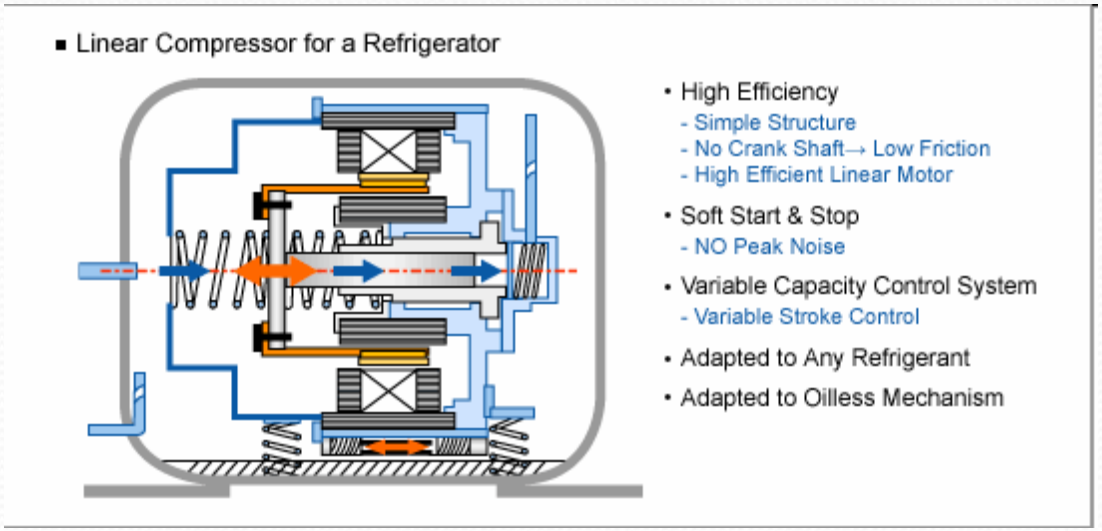


Axial + Radial lamination

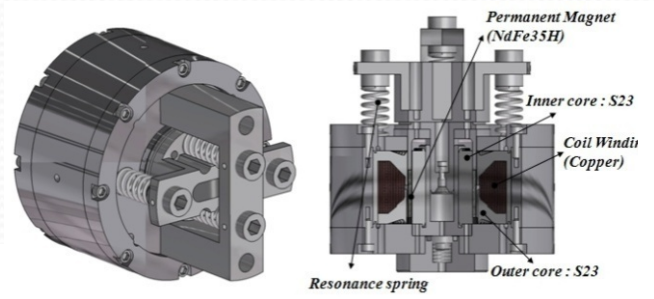
Compact high efficiency TFLM motor for reciprocating compressor



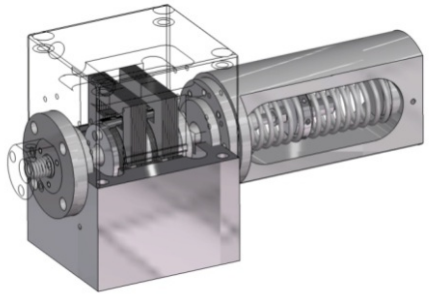
Reciprocating compressor with rotary motor



Reciprocating compressor with moving iron transverse flux linear tubular permanent magnet motor – LG electronics

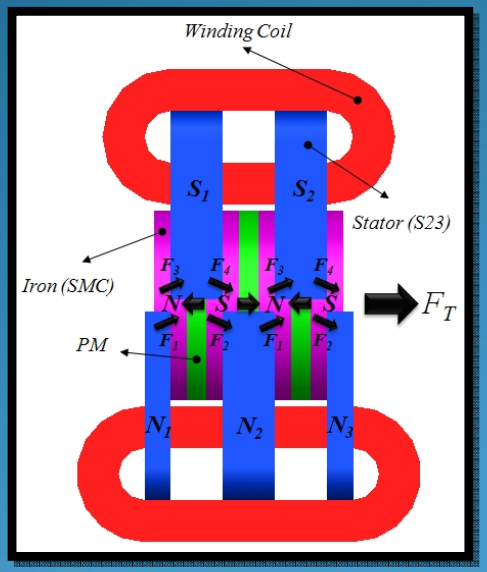


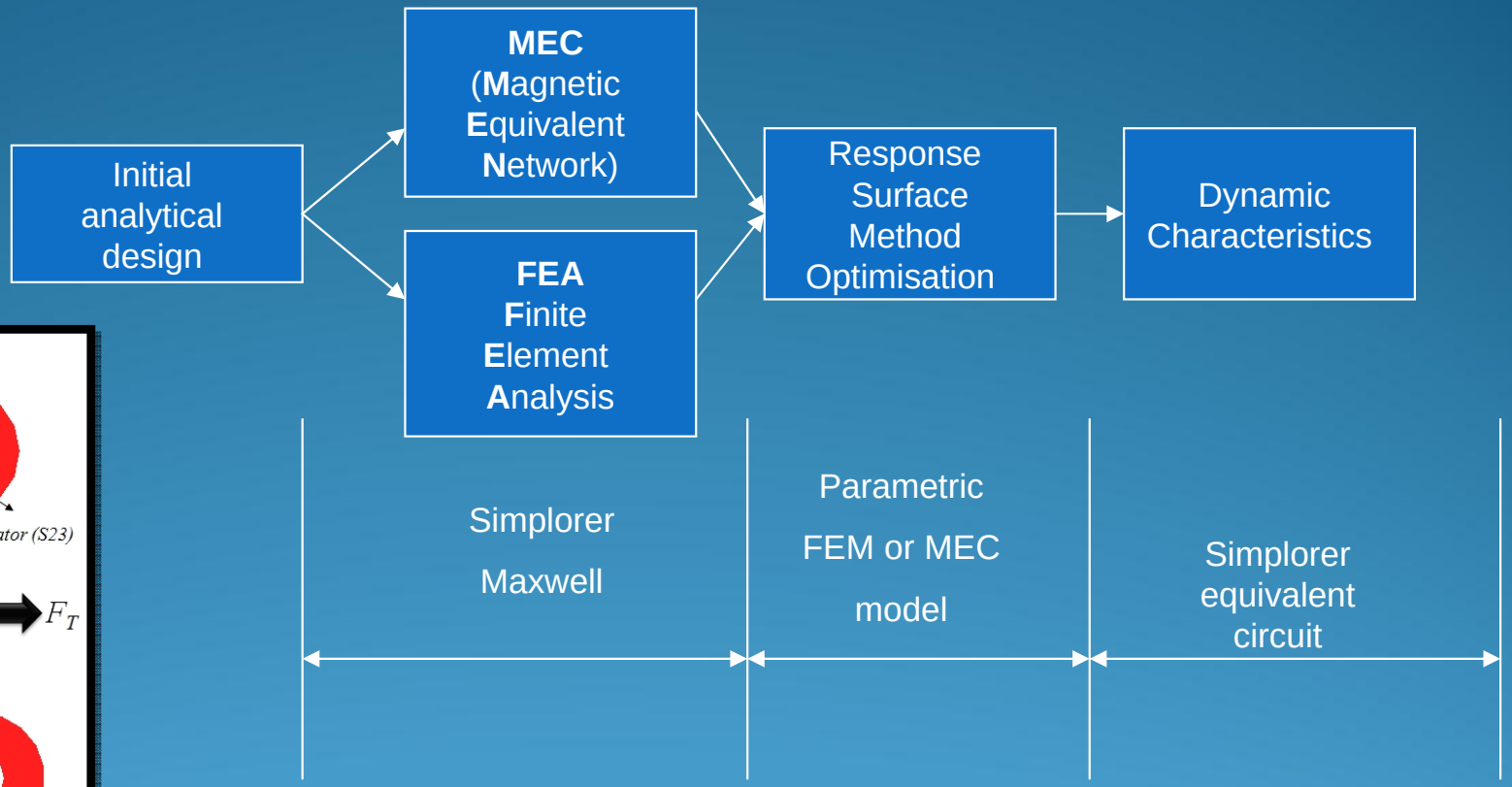
Longitudinal flux



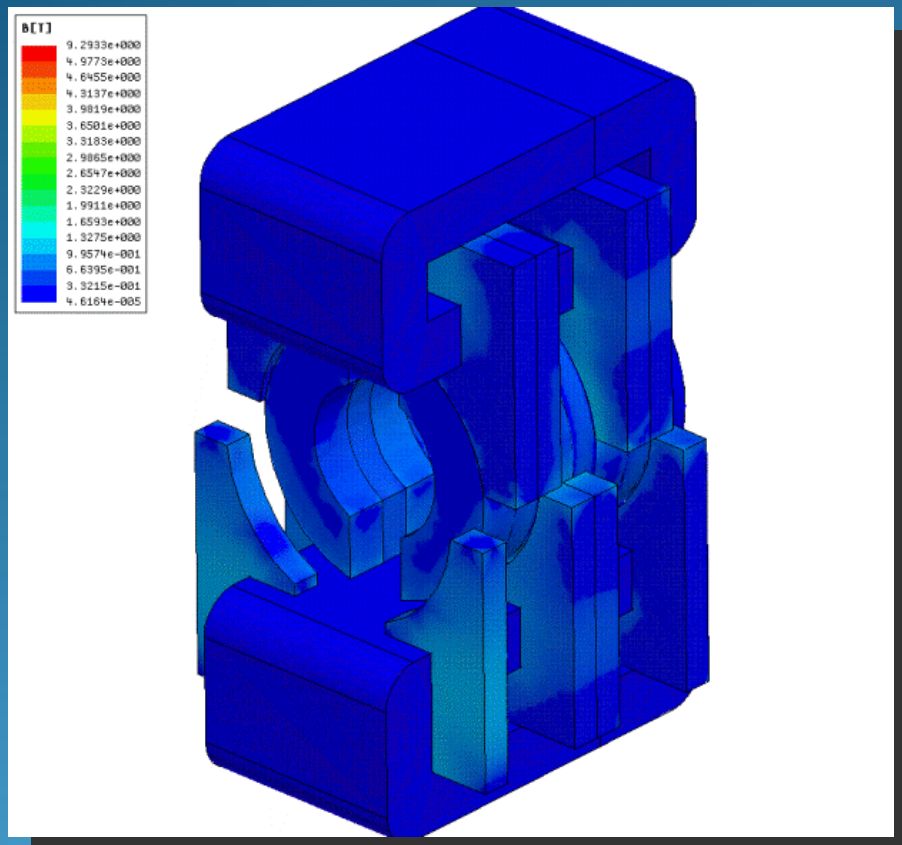
Transversal flux

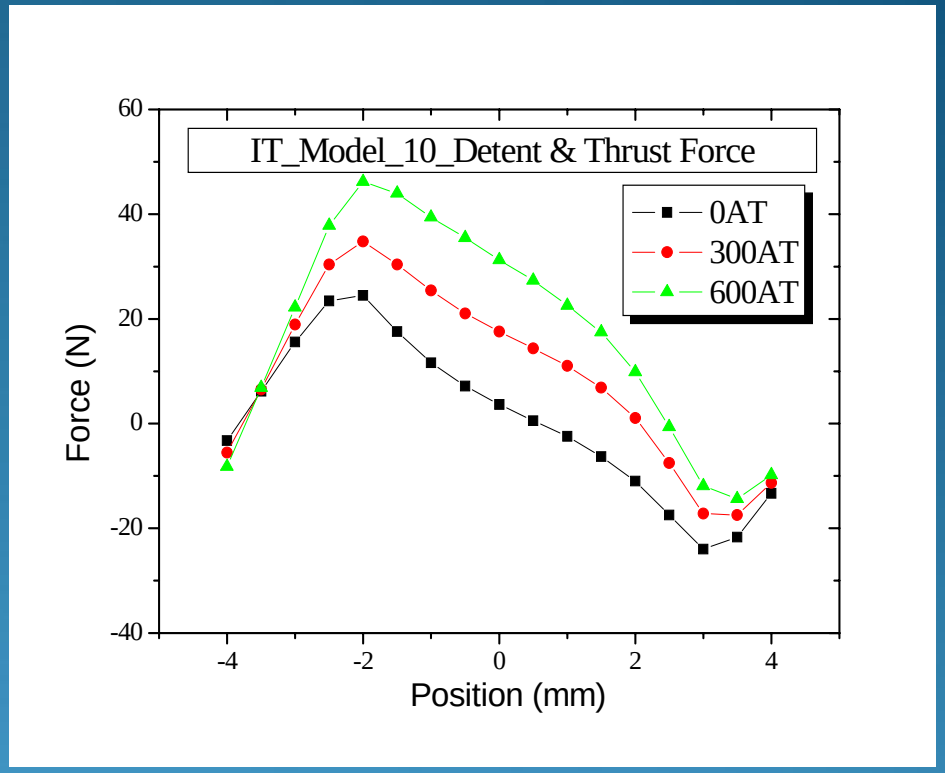
Development of high efficiency TFLM

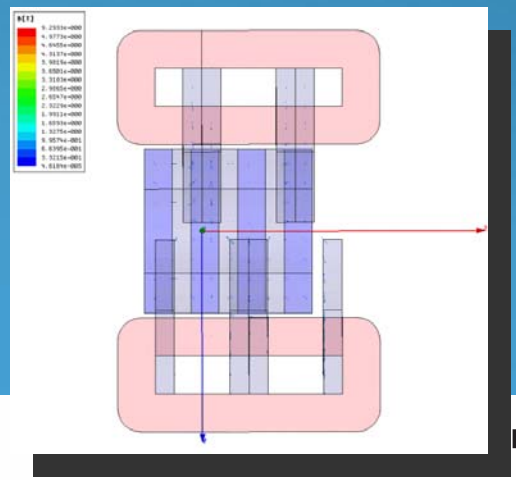




3D FEA







ANSOFT

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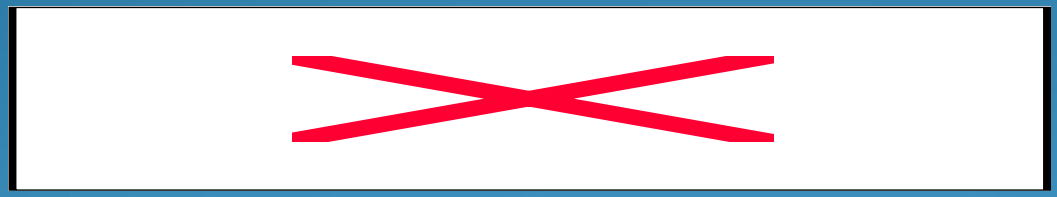
INSTITUTE

II Response Surface Optimization

RSM seeks for the relationship between design variable and response through statistical fitting method. A polynomial approximation of the model u is defined as a function of variables:



β : regression coefficients

ε : random error

The least squares method is used to estimate unknown coefficients. Matrix notations of the fitted coefficients and the fitted response model should be such as:

$$\hat{\beta} = (X'X)^{-1}X'u \qquad \hat{u} = X\hat{\beta}$$

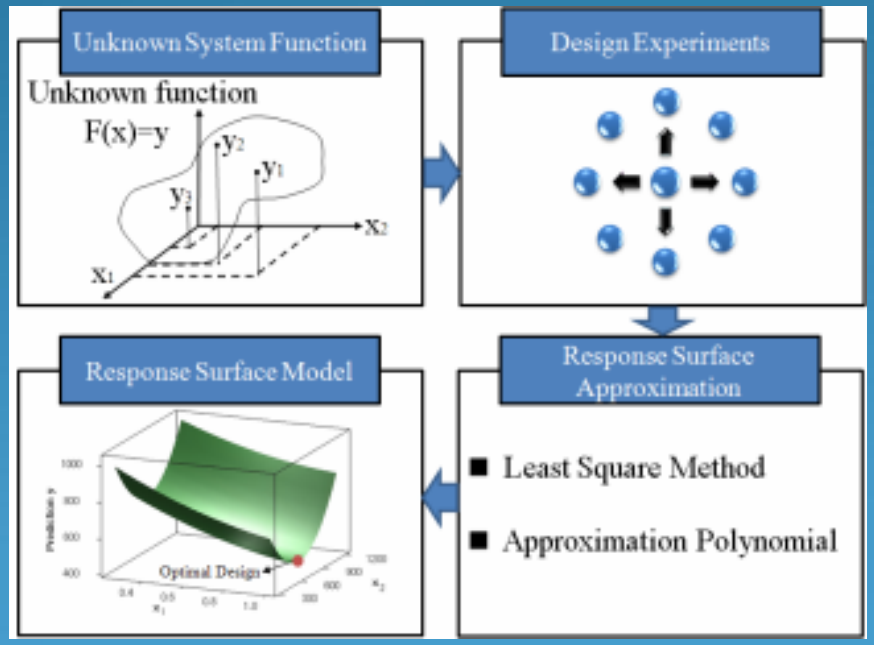
$\hat{\beta}$ is the vector of the unknown coefficients which are usually estimated to minimize the sum of the squares of the error term.

RSM method is applied in connection with FEM and the response actually represent FEM output values.

Response Surface Optimization

Computations as Optimization Method
- **Table of Orthogonal Array**
- **Finite Element Analysis (FEA)**
- **Response Surface Methodology (RSM)**
- **Optimum Algorithm**

Response Surface Method

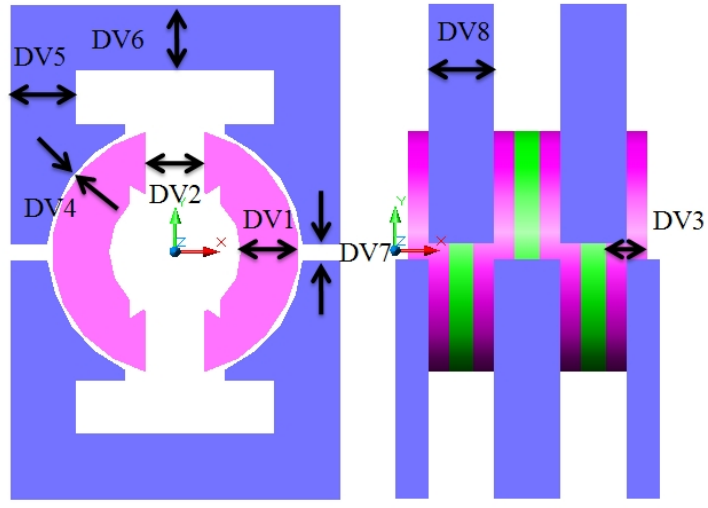


Optimization : TFLM

Set Design Variable & Level
Table of Orthogonal Array Simulation (2-D FEA)
Calculation Total Weight Peak Detent/Thrust force
Apply Optimum Algorithm
Make Multiple Regression Adjust coefficients of multiple determination R^2_{adj}
Optimum Solution/Response Surface
Verify Optimum Solution

Procedure of DOE

Design variables and levels



Geometry parametrized model

TABLE I DESIGN VARIABLE AND LEVEL

Design variable / Level	*DV1*	*DV2*	*DV3*	*DV4*	*DV5*	*DV6*	*DV7*	*DV8*
1	*5*	*5*	*4*	*0.3*	*5*	*5*	*2*	*5*
2	*8*	*9*	*6*	*0.5*	*8*	*8*	*5*	*8*

Table II Table orthogonal array and response

Exp.	*DV1*	*DV2*	*DV3*	*DV4*	*DV5*	*DV6*	*DV7*	*DV8*	Max. thrust force(N)	Max. detent force(N)	Weight (kg)
1	5	5	6	0.3	8	8	2	8	41.788	8.3283	0.232833
2	5	5	4	0.5	8	5	5	8	37.306	16.488	0.193078
3	8	9	4	0.3	8	5	2	8	81.923	57.706	0.233808
4	5	9	6	0.5	5	5	2	5	24.188	6.6405	0.118522
5	5	5	4	0.3	8	5	2	5	48.025	27.054	0.146973
6	8	5	6	0.3	8	5	5	8	61.292	29.643	0.254114
7	5	9	4	0.5	8	8	2	5	44.776	23.971	0.156495
8	5	9	4	0.5	5	8	2	8	39.414	15.069	0.178034
9	8	9	4	0.5	8	5	5	5	42.514	24.251	0.181876
10	8	9	4	0.5	5	5	5	8	63.276	42.174	0.191931
11	8	9	6	0.5	5	8	5	5	36.022	3.5496	0.181009
12	8	5	4	0.5	8	8	2	8	62.506	32.761	0.278601
13	5	9	4	0.3	8	8	5	8	48.51	20.459	0.213792
14	8	5	4	0.3	8	8	5	5	75.534	44.581	0.215958
15	8	9	6	0.3	8	8	2	5	56.636	10.206	0.210025
16	8	5	6	0.5	8	5	2	5	32.183	7.9143	0.206771
17	8	5	4	0.5	5	8	2	5	47.665	22.198	0.189028
18	5	5	6	0.5	5	8	5	8	27.191	7.3401	0.189149
19	5	5	4	0.5	5	5	5	5	35.094	17.507	0.122518
20	8	9	6	0.3	5	8	2	8	57.853	31.64	0.226134
21	5	9	4	0.3	5	8	5	5	45.169	24.326	0.129265
22	5	9	6	0.3	8	5	5	5	33.241	6.5502	0.138029
23	8	9	4	0.3	5	5	2	5	47.162	19.963	0.158467
24	5	9	6	0.3	5	5	5	8	36.619	10.491	0.153371
25	8	5	6	0.3	5	5	5	5	48.78	13.522	0.181276
26	8	5	6	0.5	5	5	2	8	45.443	23.139	0.215575
27	8	5	4	0.3	5	8	5	8	68.257	56.159	0.233262
28	5	5	6	0.3	5	8	2	5	38.38	4.6401	0.144941
29	5	5	4	0.3	5	5	2	8	52.811	26.675	0.161983
30	5	5	6	0.5	8	8	5	5	28.498	11.349	0.167222
31	5	9	6	0.5	8	5	2	8	27.13	6.6808	0.19239
32	8	9	6	0.5	8	8	5	8	41.662	11.715	0.268137

OPTIMUM DESIGN RESULTS

- function to draw response surface:

Thrust function

$$Y_{Thrust} = -44.847 - 1.79DV1 - 1.018DV2 + 1.957DV3 + 57.369DV4 + 8.41DV5 + 7.376DV6 + 4.752DV7 + 8.537DV8 - 7.066DV1DV4 + 0.306DV1DV5 + 0.321DV1DV7 + 0.857DV1DV8 - 0.155DV2DV6 + 0.253DV2DV8 - 0.714DV3DV5 - 0.563DV3DV8 - 11.174DV4DV5 + 0.413DV5DV6 - 0.471DV5DV7 - 0.385DV5DV8 - 0.242DV6DV7 - 1.113DV6DV8 - 0.425DV7DV8$$

Detent function

$$Y_{Detent} = -86.838 + 2.489DV1 - 0.917DV2 - 1.8DV3 + 67.508DV4 + 15.074DV5 + 6.031DV6 + 7.085DV7 + 6.968DV8 - 0.184DV1DV2 - 0.921DV1DV3 - 11.288DV1DV4 + 0.256DV1DV7 + 1.555DV1DV8 + 0.257DV2DV8 + 14.316DV3DV4 - 0.662DV3DV5 - 0.533DV3DV7 - 4.083DV4DV5 - 10.89DV4DV8 - 0.246DV5DV6 - 0.482DV5DV7 - 1.006DV5DV8 - 0.708DV6DV8 - 0.425DV7DV8$$

Weight function

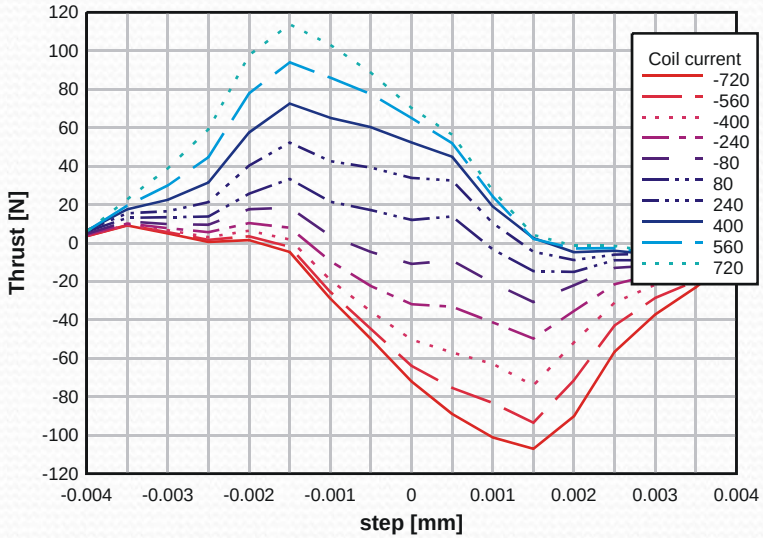
$$Y_{Weight} = 3.21E-2 + 1.13E-2DV1 - 7.28E-4DV2 - 8.35E-4DV3 - 6.66E-3DV4 - 4.57E-3DV5 - 2.16E-3DV6 - 4.61E-4DV7 - 8.74E-4DV8 - 3.47E-4DV1DV2 + 4.03E-4DV1DV3 + 5.73E-4DV1DV4 + 3.08E-4DV1DV5 - 6.8E-5DV1DV6 + 1.55E-4DV1DV7 - 1.41E-4DV1DV8 + 7.19E-5DV3DV5 + 1.42E-4DV3DV7 + 4.11E-4DV4DV5 - 1.9E-4DV4DV8 + 4.01E-4DV5DV6 - 2.05E-4DV5DV7 + 1.65E-3DV5DV8 + 1.17E-3DV6DV8 - 1.17E-4DV7DV8$$

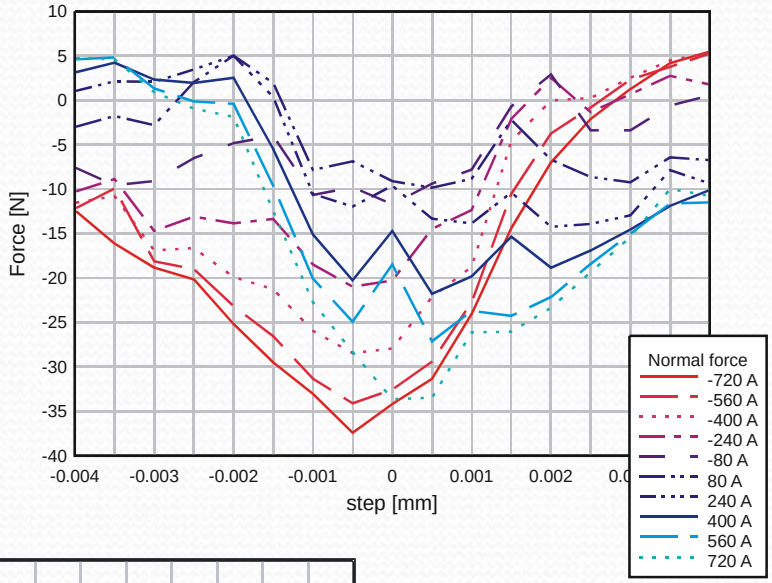
COMPARISON OF INITIAL MODEL AND OPTIMUM MODEL

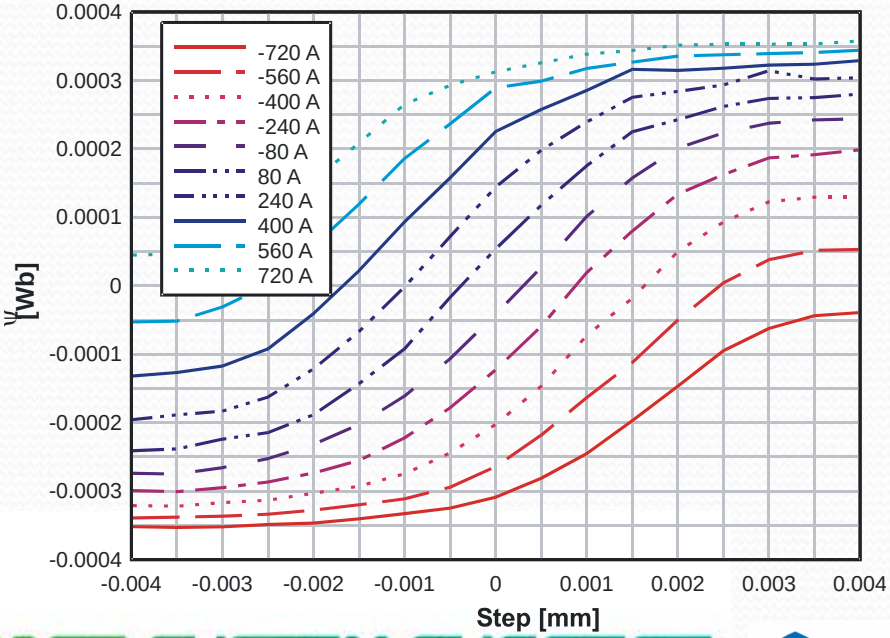
Table III Optimal model comparison

Model	Weight[kg]	Thrust force[N]	Detent force[N]
Initial design	0.254	61.292	29.643
Optimum (predicted)	0.22	67	28.318
3-D FEM	0.22	67.905	27.764
Variation between initial and 3-D FEM model %	-15.454	8.519	-6.767

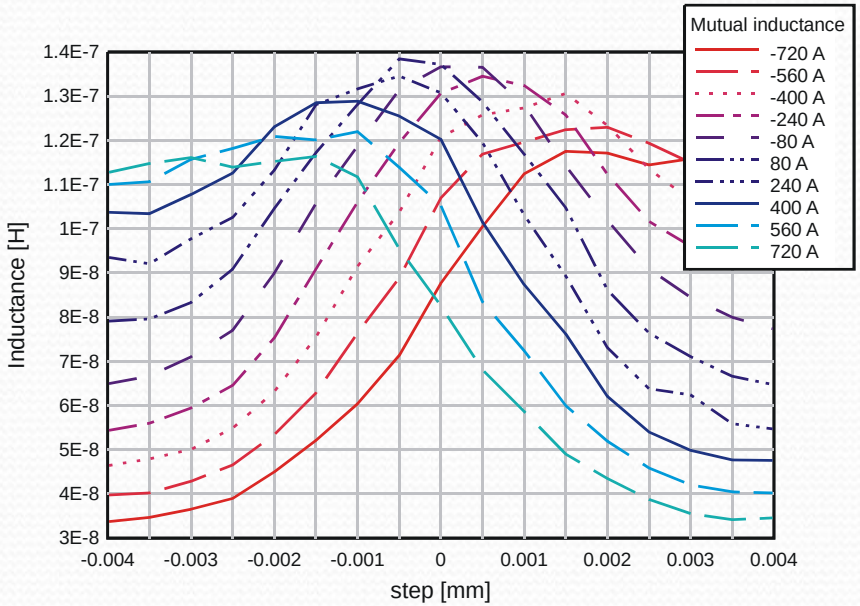
Optimal prototype characteristics
FEA

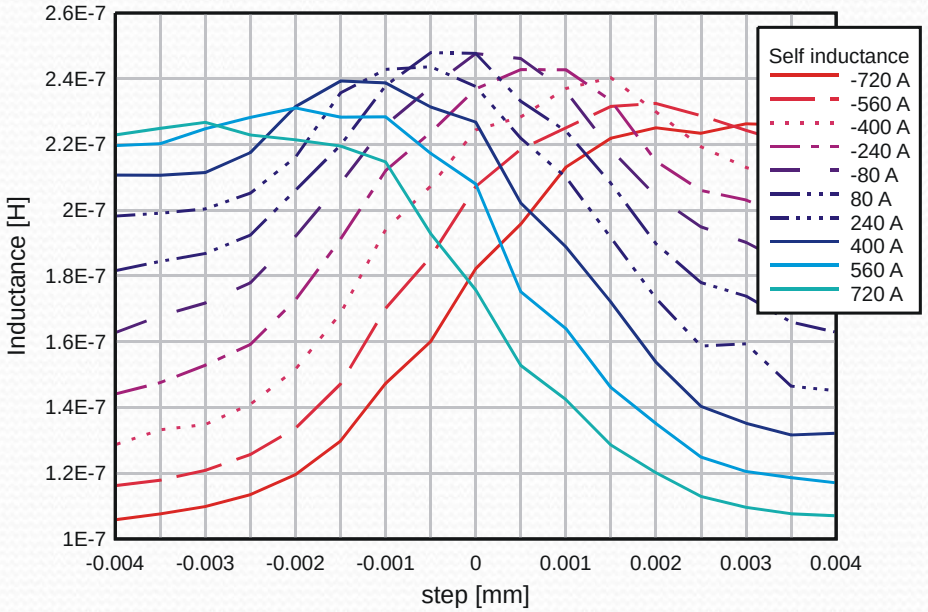




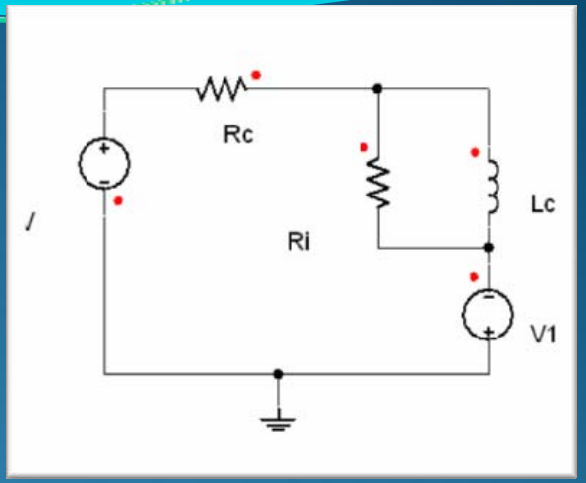


Optimal prototype characteristics FEA



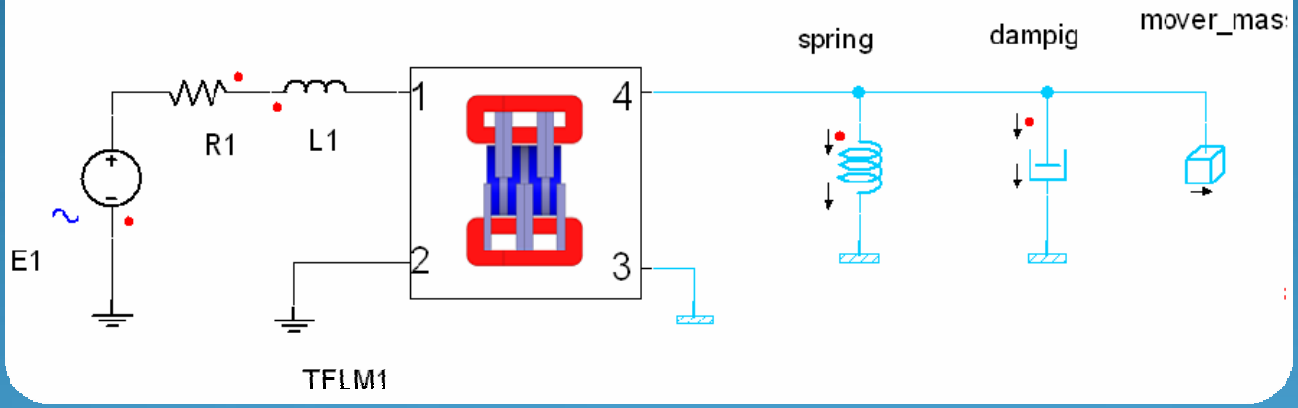


IV Dynamic Characteristics

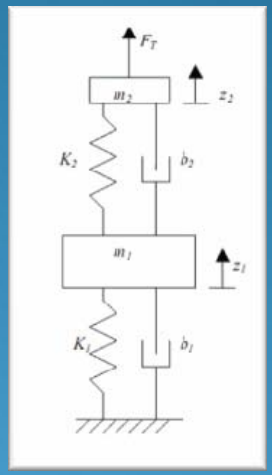


Electrical system

Transverse flux linear reciprocating motor



No load model



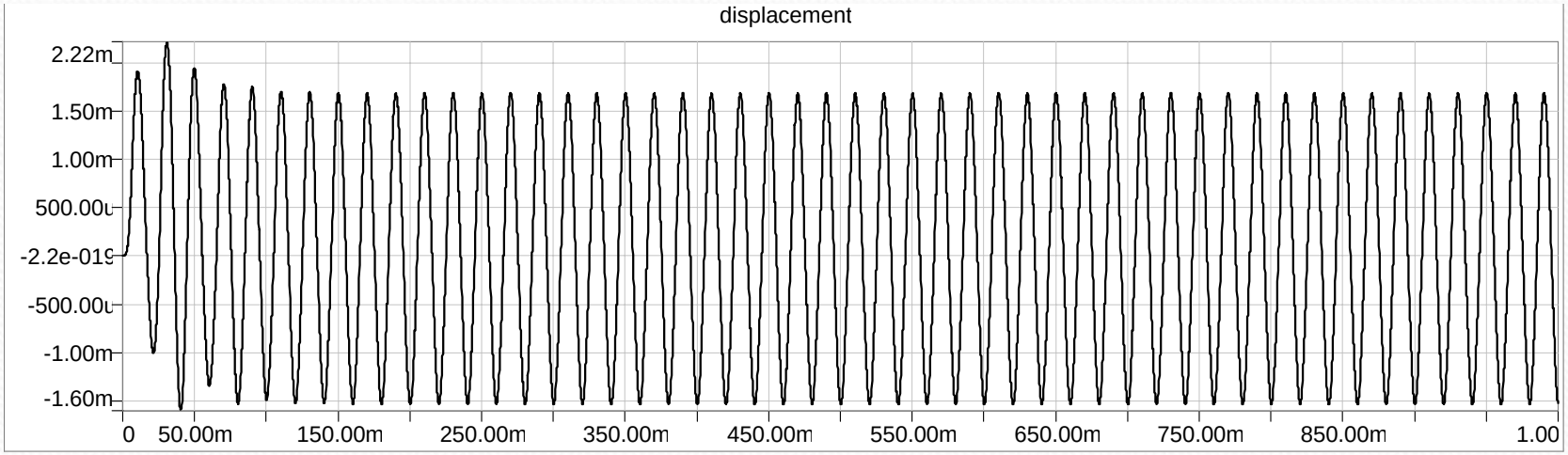
Piston

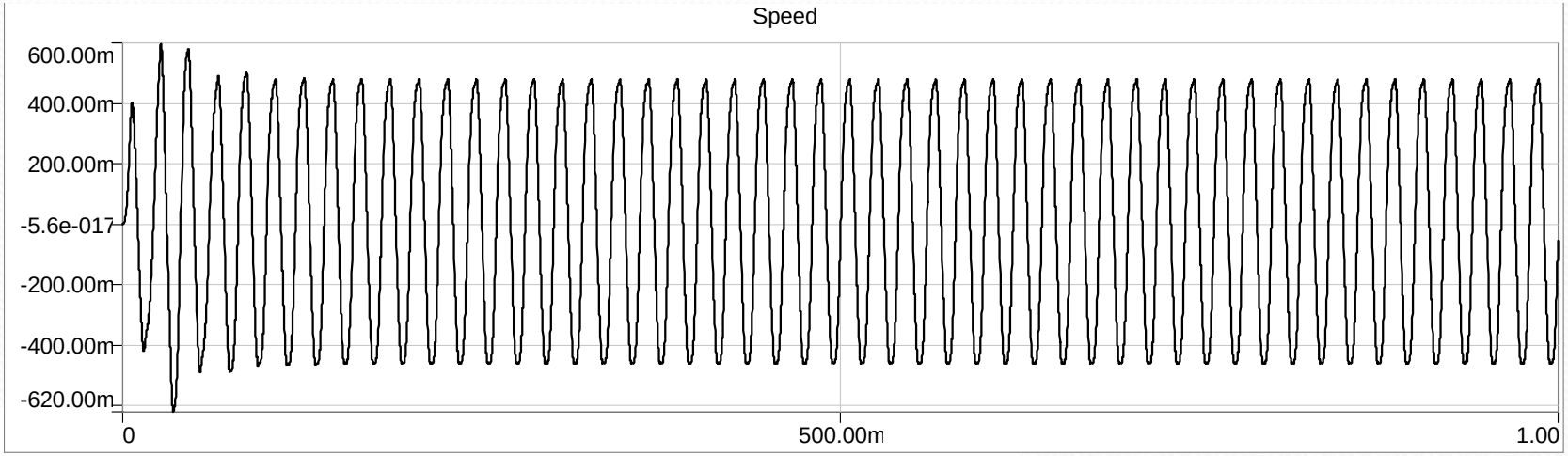
Mover

Mechanical system

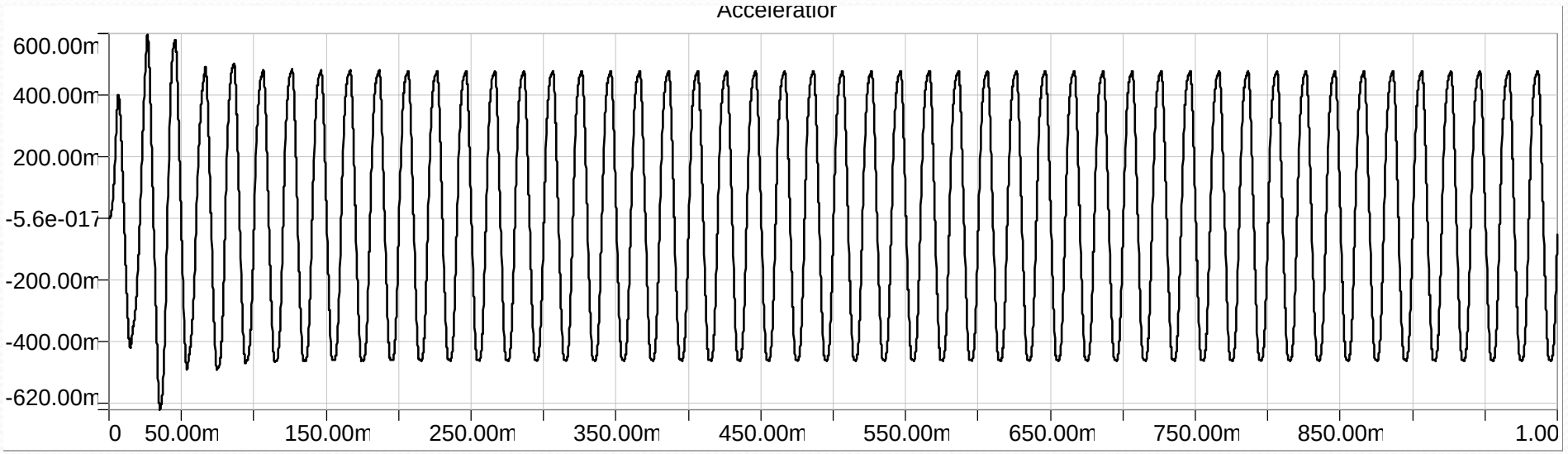
$$\begin{cases} m_1\ddot{z}_1 + (b_1+b_2)\dot{z}_1 - b_1\dot{z}_2 + (K_1+K_2)z_1 - K_1 z_2 = 0 \\ m_2\ddot{z}_2 - b_2(\dot{z}_1 - \dot{z}_2) - K_2(z_1 - z_2) = F_T \end{cases}$$

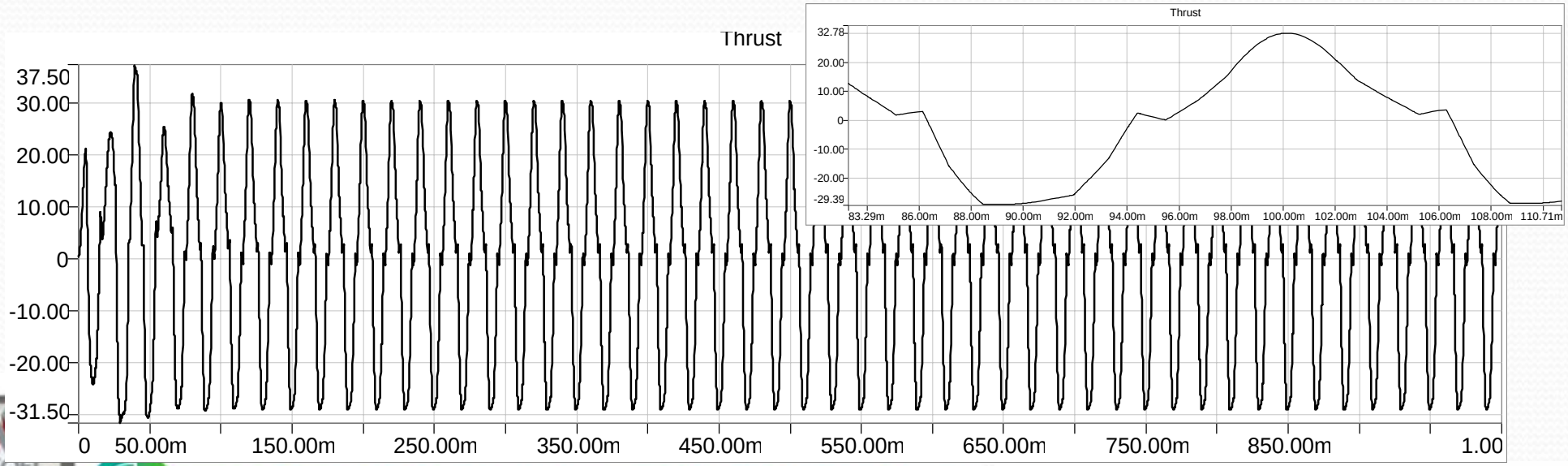
Simulation results I no load



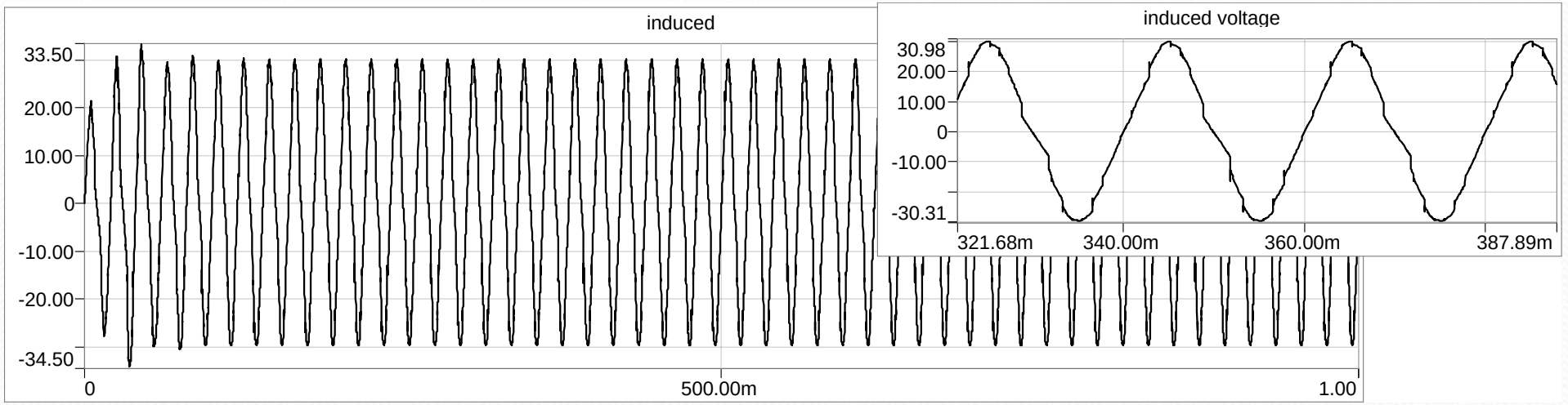


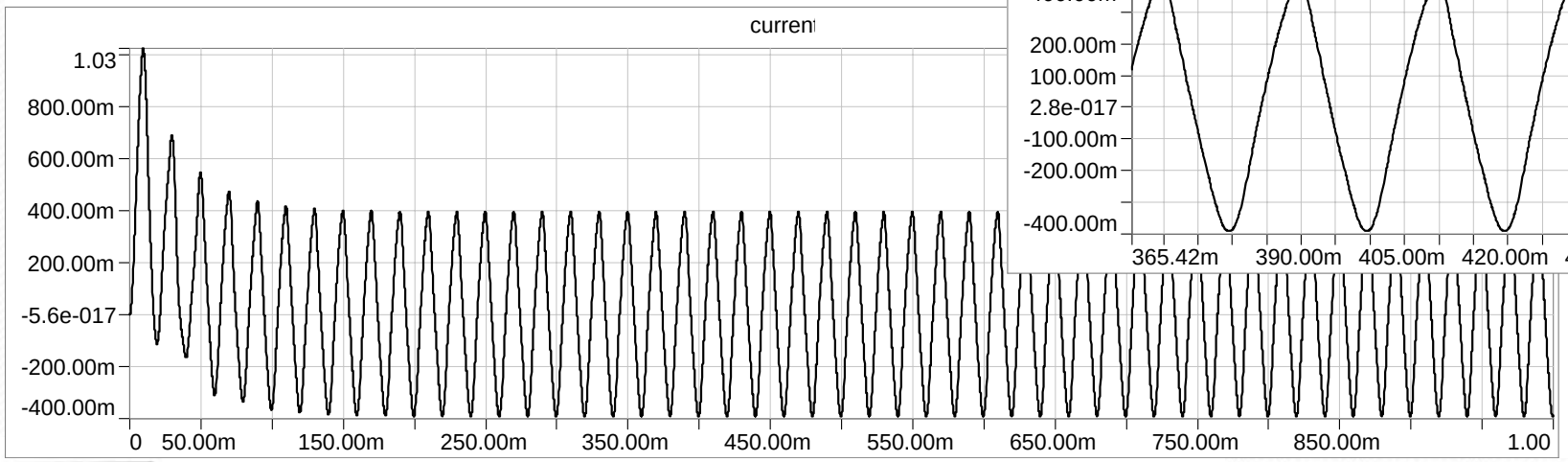
Simulation results II no load



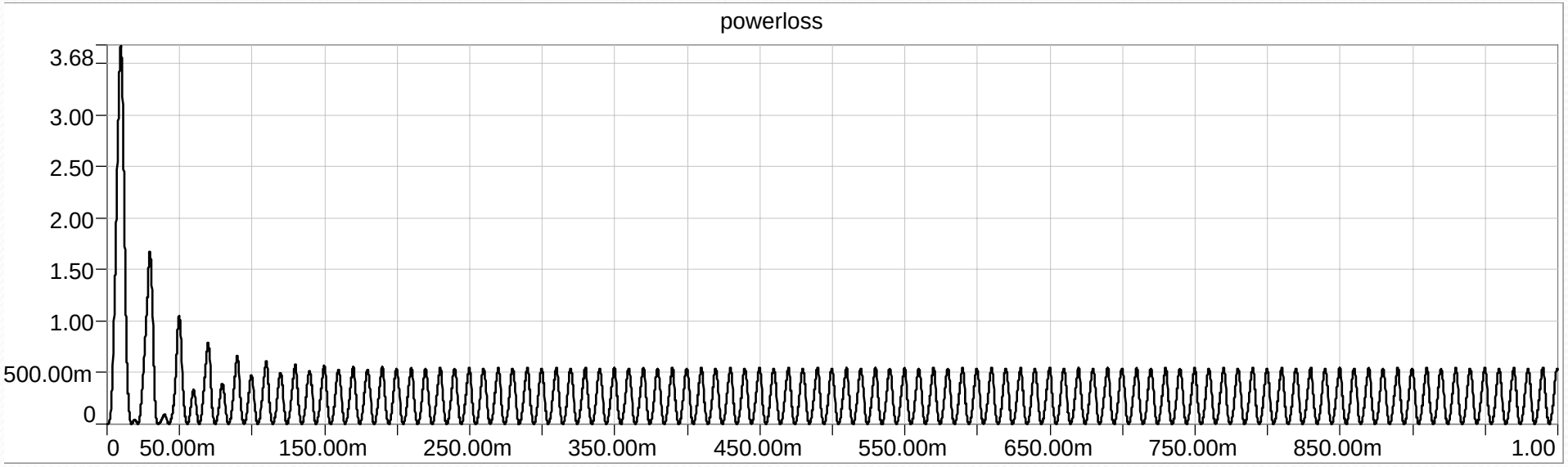


Simulation results III

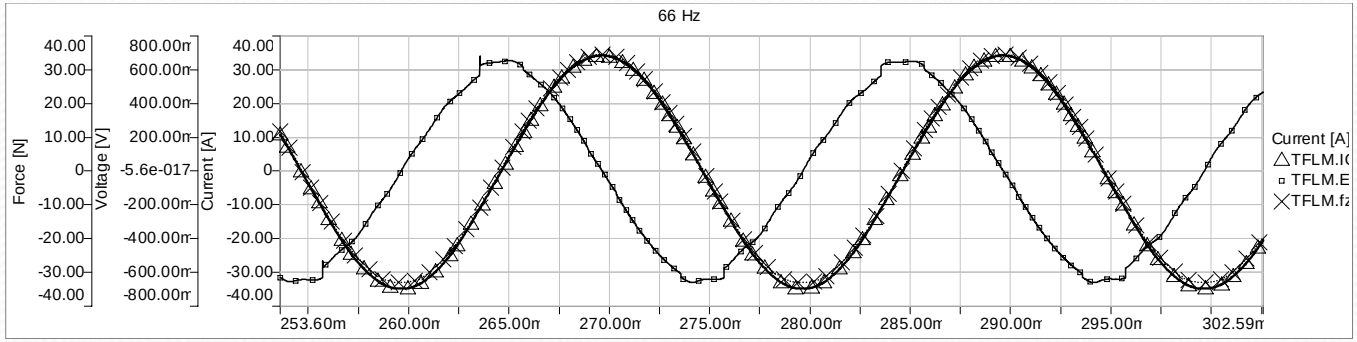


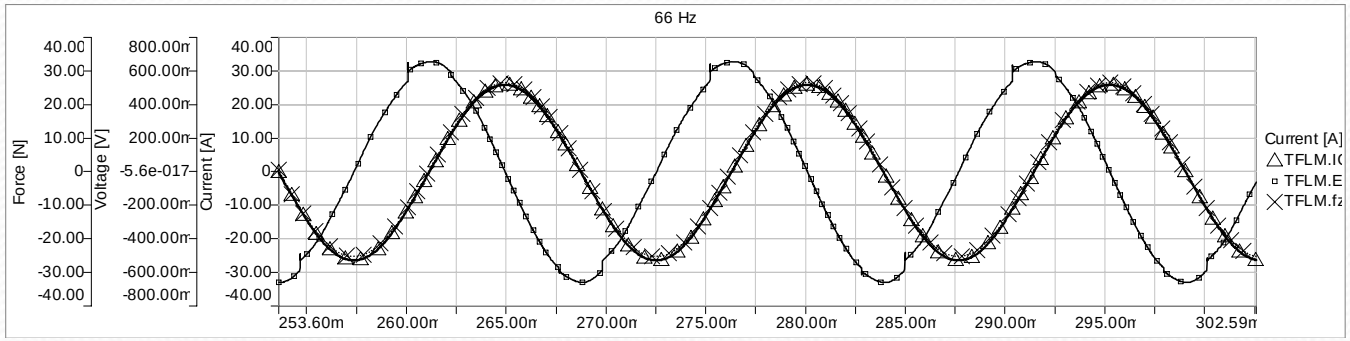


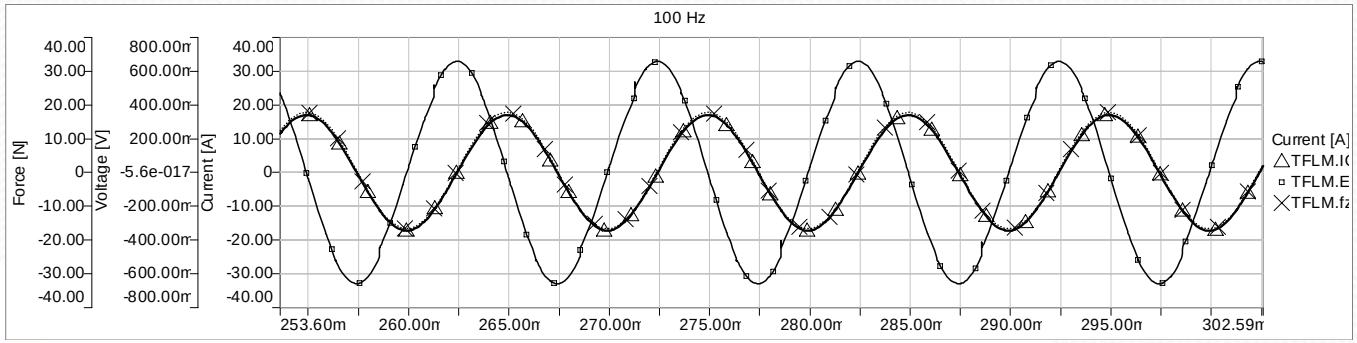
Simulation results IV no load



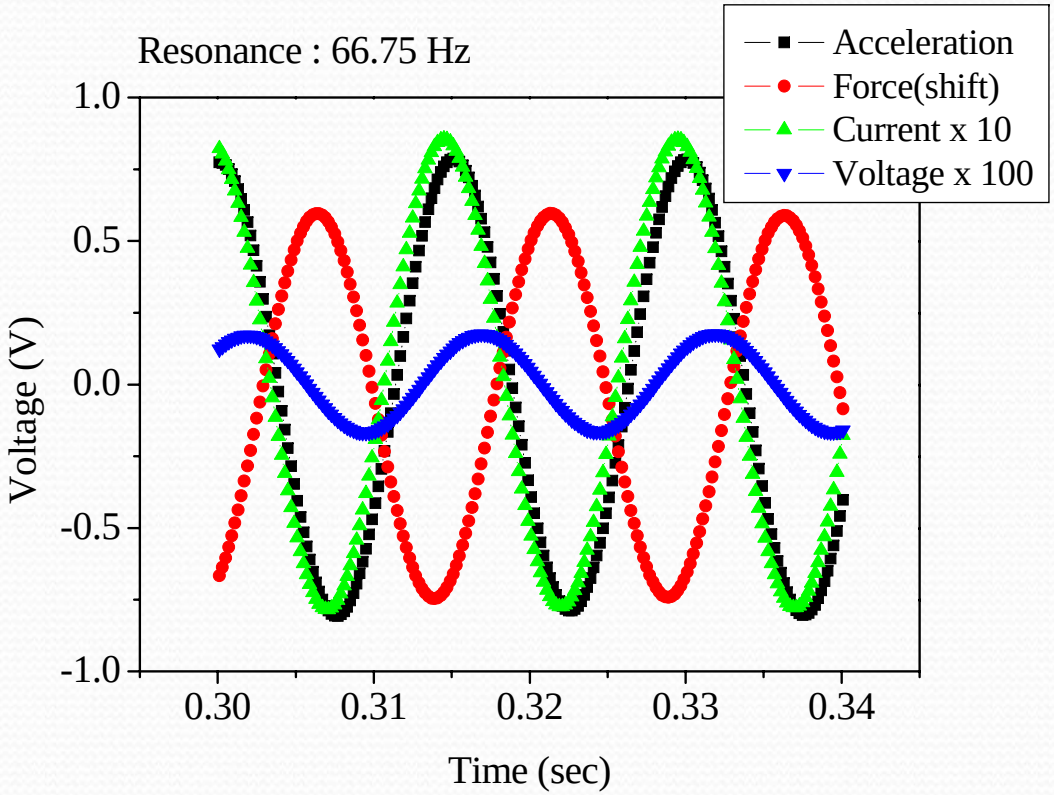
Simulation results IV load

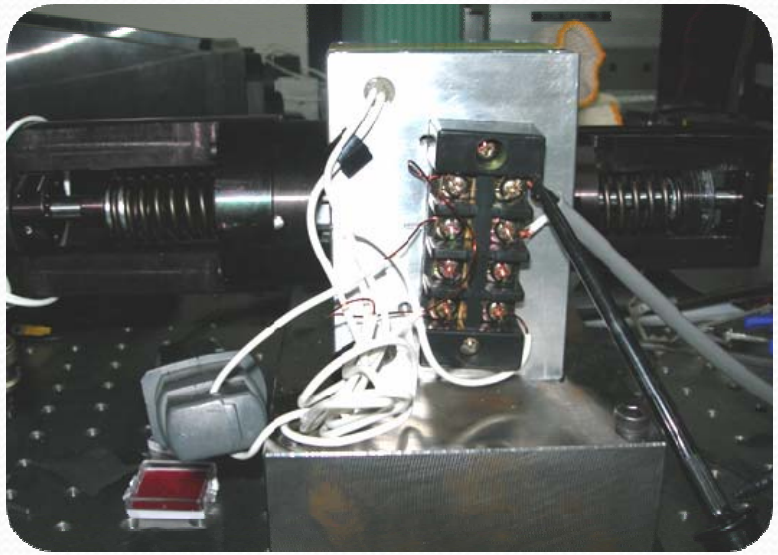






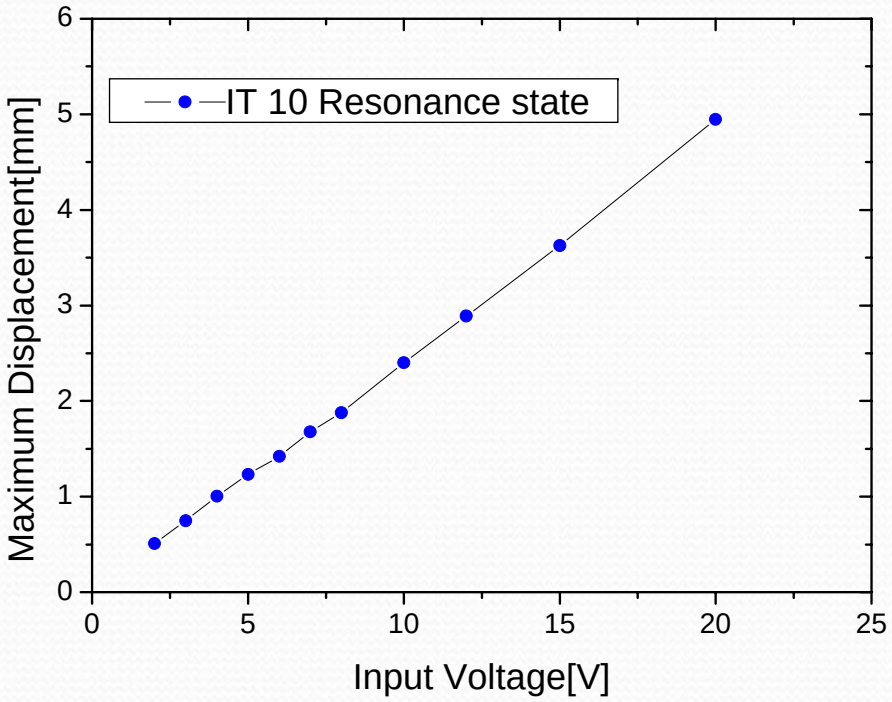
Experimental results

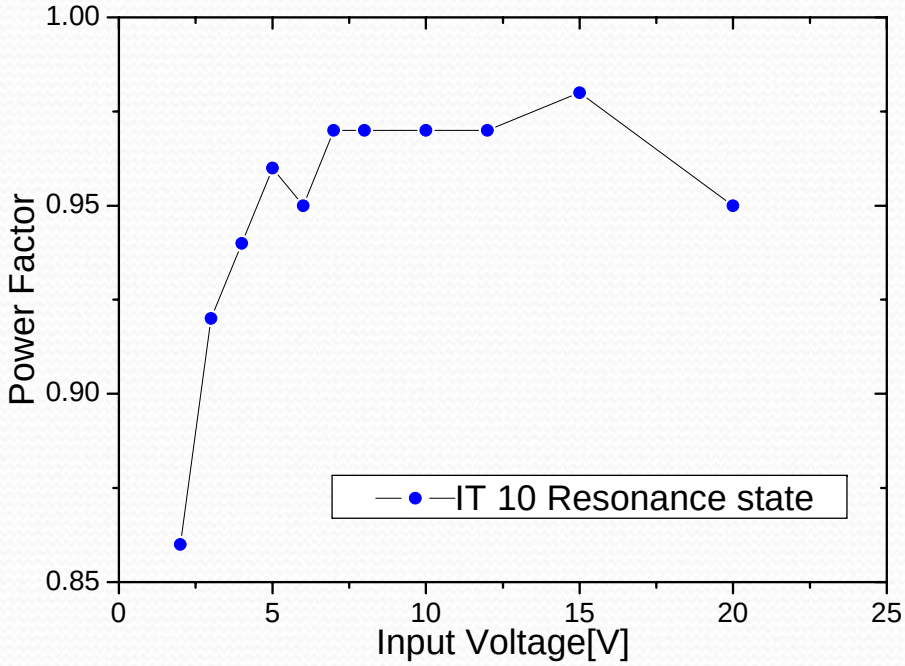




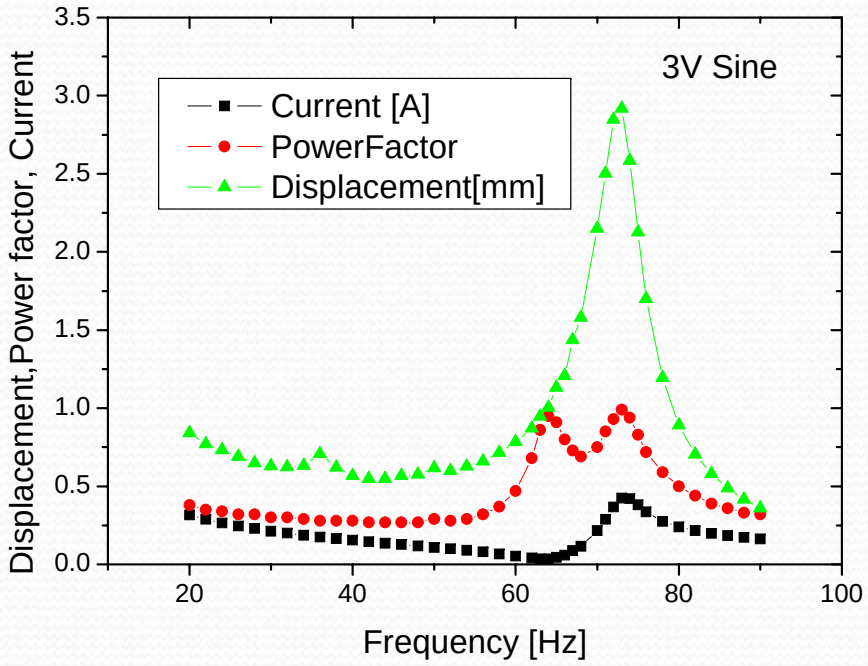
Manufactured prototype

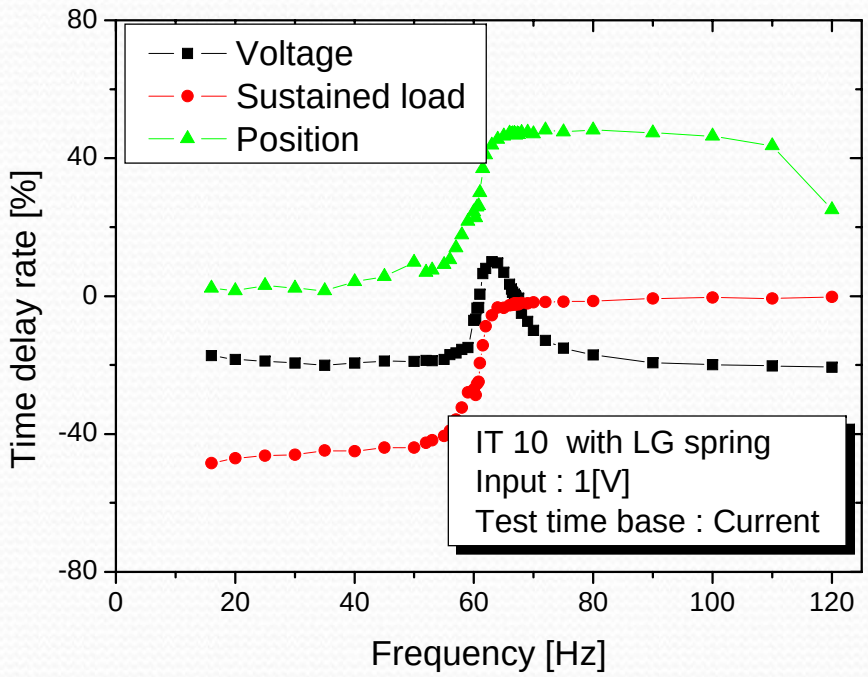
Experimental results II

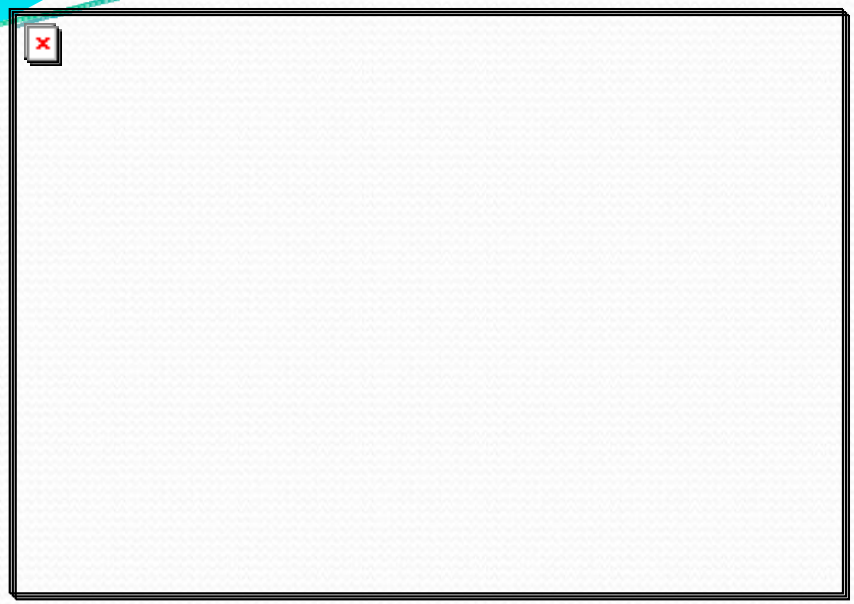




Experimental results III







Thank you