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Toyota Prius Brushless IPM Motor Optimization

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Contents

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Introduction

Motivation

Motor background

Motivation

- **Toyota prius**
  - Hybrid vehicle
    - The ride quality is improved by using motor compared to ICE vehicle

- **Interior Permanent Magnet(IPM) motor**
  - Advantage
    - Large speed range
    - High motor torque at same current
  - Disadvantage
    - High cogging torque
    - High torque ripple
    - High vibration and noise

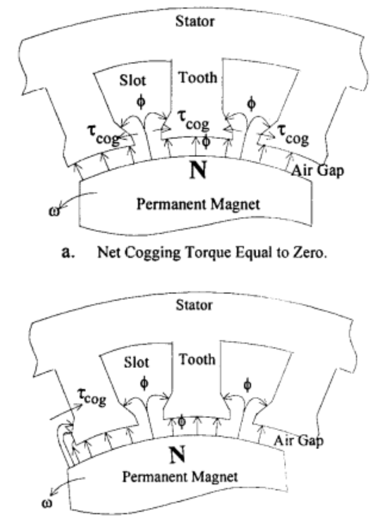
(High cogging torque, High torque ripple) → Interrupt hybrid vehicle concept (smooth ride)

↓

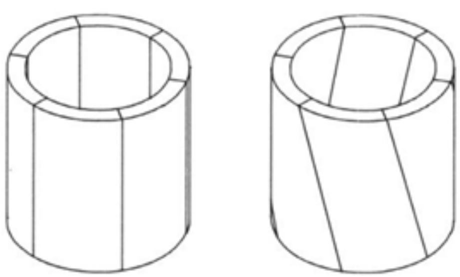
Using optimization, improve the disadvantage of IPM motor that interrupt hybrid vehicle concept and motor losses

Motor background

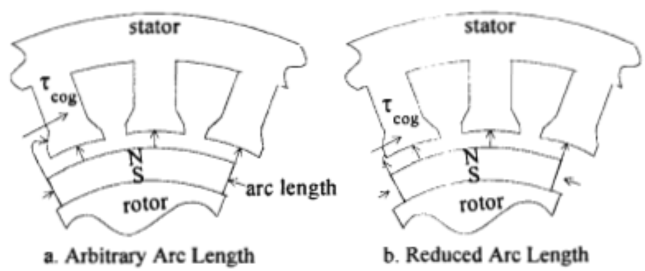
- **Cogging torque**
  - The torque due to the interaction between the rotor permanent magnet and the stator slots of a permanent magnet machine
  - Known as detent or no-current torque
  - Reducing techniques*
    - Skewing stator stack or magnets
    - Varying the magnet arc length
    - Varying the radial shoe depth



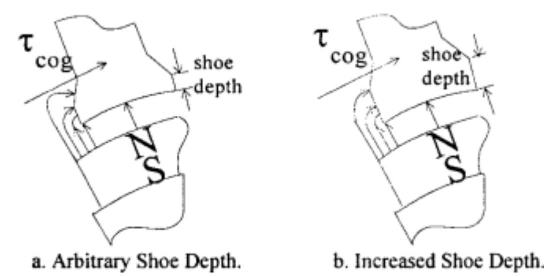
[cogging torque production]



[skewing matnet]



[variation in the magnet arc length]



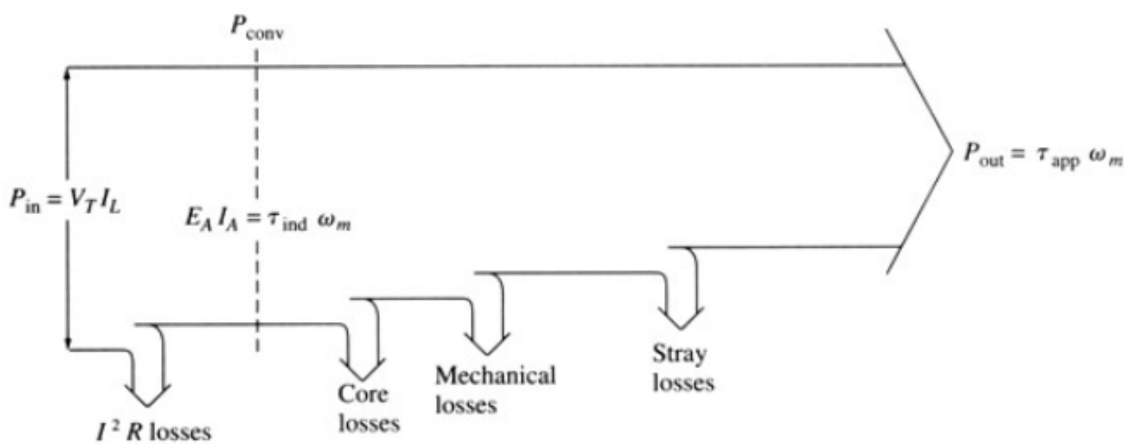
[variation in the radial shoe depth]

- **Torque ripple**
  - Motor torque amplitude at power applied
  - $T_{max} - T_{min}$

*Keyhani, CB Studer, T. Sebastian, SK Murthy, A. (1999). Study of cogging torque in permanent magnet machines. *Electric Machines &Power Systems*, *27*(7), 665-678.

Motor background

- **Motor losses**
  - Joule losses(Copper losses)
    - Joule heating (I^2R) when current flows through stator coils and rotor
  - Iron losses(Core losses)
    - Due to changing magnetic field in the rotor and stator cores
  - Mechanical losses
    - Losses associated with mechanical effects
  - Stray(miscellaneous) losses



[Motor power-flow diagram]

Flux®

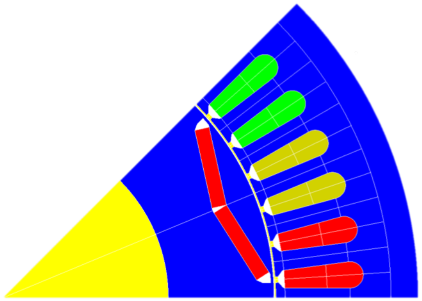
EM analysis

Initial motor

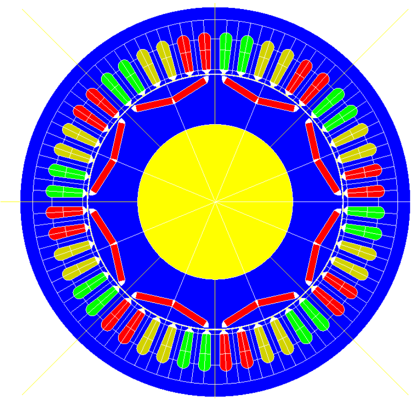
No-current simulation

Constant speed simulation

Initial motor



- **Motor rating**
  - Motor designed for hybrid electric vehicle traction/generation
    - Max bus voltage : $500\ \mathrm{V}$
    - Peak torque : $400\ \mathrm{N \cdot m}$
    - Max speed : $6000\ \mathrm{rpm}$
    - Peak power rating : $50\ \mathrm{kW}\ at\ 1200 - 1500\ \mathrm{rpm}$



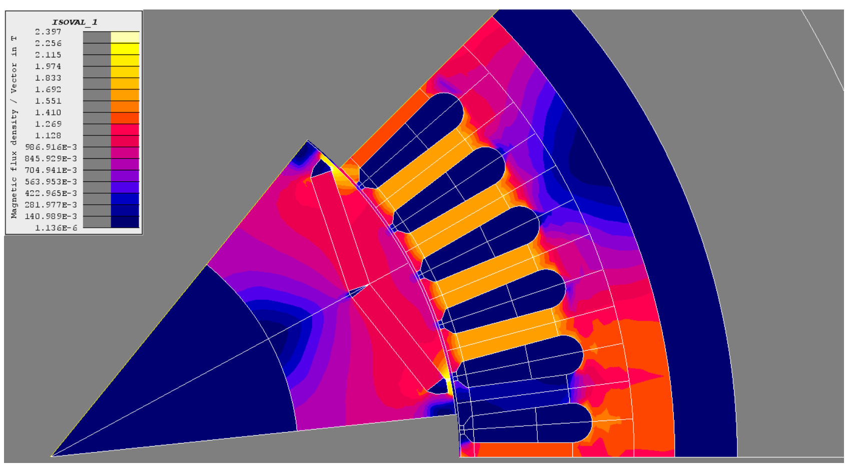
- **Motor main characteristics**
  - 48 stator slots
  - 3 phase wye connected
  - 4 pole pairs
  - Stator outer radius : $141\ \mathrm{mm}$
  - Stack length : $75\ \mathrm{mm}$
- **Material**
  - Lamination type : M270-35A

Material	B(H)		J(E) $[\Omega \mathrm{m}]$
	Remanent flux density	Relative permeability	
NDFEB	1.2	1.05	1.4e-6

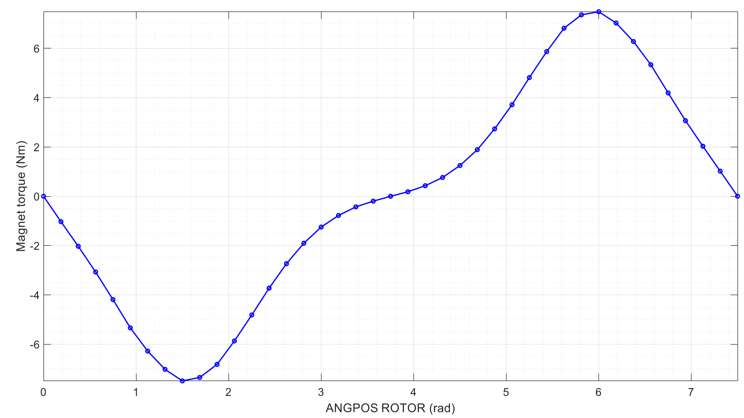
No-current simulation

- **Condition**
  - 1/6 rpm constant speed
  - Simulation range: $0^{\circ} - 7.5^{\circ}$
  - Simulation steps: 40
  - Cogging torque is computed with a multi-position simulation

- **Initial motor result**
  - Cogging torque : $7.4874\ \mathrm{N \cdot m}$



[Magnetic flux density]

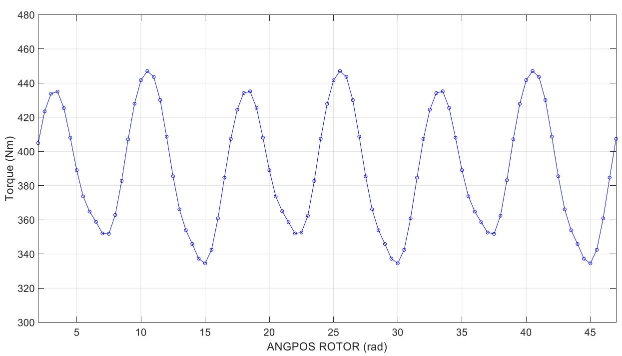


[Motor torque]

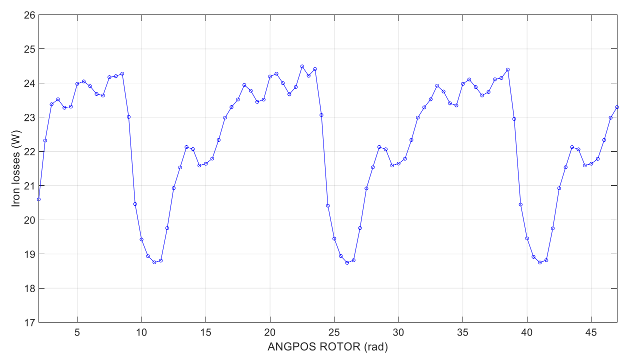
Constant speed simulation

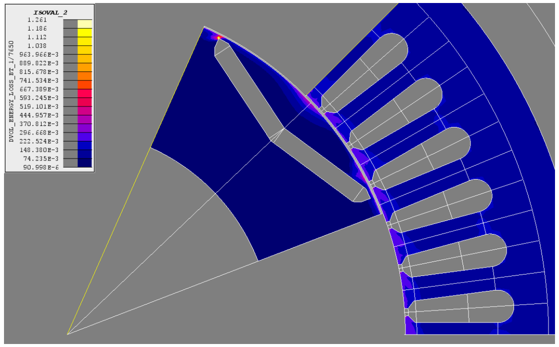
- **Condition**
  - 1200 rpm constant speed
  - Simulation range: $0^{\circ} - 47^{\circ}$
  - Simulation steps: 94
  - Max current: 200A

- **Initial motor result**
  - Torque ripple : $T_{max} - T_{min} = 112.62\ \mathrm{N \cdot m}$
  - Average iron losses : 22.28W

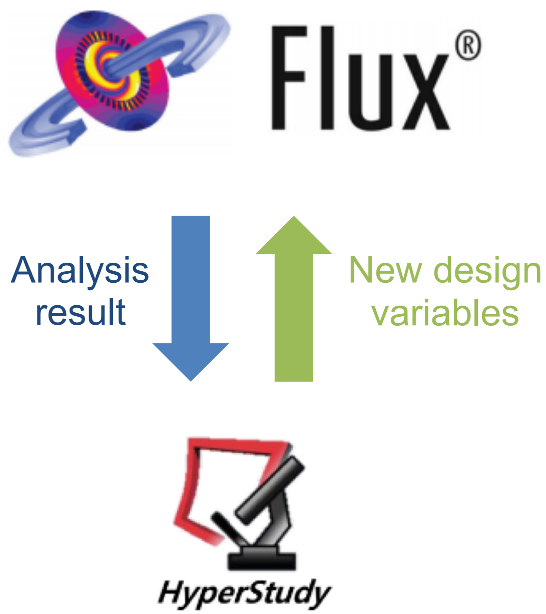


[Motor torque]





[iron losses]



Optimization

- Process flowchart
- Formulation
- Surrogate model
- Design of experiment (1)
- Data analysis & screening
- Design of experiment (2) & fitting
- Optimization

Process flowchart

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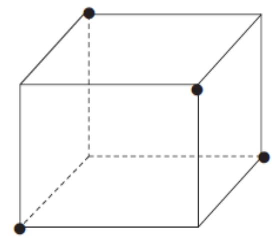
Formulation	
Objective function	minimize f
Design variables	GAP, RADSH, ⋯ 15 design variable
constraint	$\mathrm{GAP} \geq 0.6\ \mathrm{mm}$ $\mathrm{BRIDGE} \geq 1\ \mathrm{mm}$ $\mathrm{A}_{\mathrm{magnet}} \leq \widehat{\mathrm{A}}_{\mathrm{magnet}}$ $\mathrm{T}_{\mathrm{peak}} \geq 0.95 \cdot \widehat{\mathrm{T}}_{\mathrm{peak}}$

Design of experiment (1)



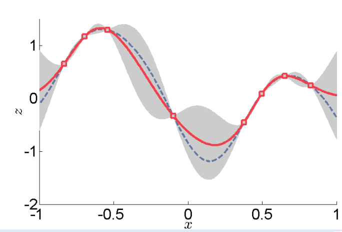
[DoE(FFD)]

Screening

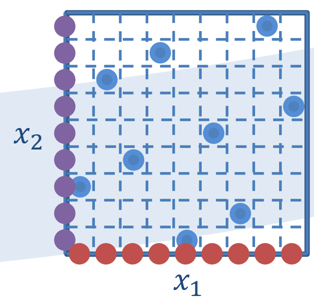
	Variables	Degrees of Freedom	Sum of Squares	Mean Squares	Mean Squares Percent	F-value	p-value
1	GAP	1	75.059516	75.059516	4.6096707	3.4379855	0.0691779
2	RADSH	1	5.8990578	5.8990578	0.3622820	0.2701973	0.6053239
3	LM	1	70.750954	70.750954	4.3450667	3.2406385	0.0774194
4	WEB	1	0.0063110	0.0063110	3.88e-04	2.89e-04	0.9864977
5	MAGWID	1	239.56246	239.56246	14.712379	10.972790	0.0016541
6	BRIDGE	1	0.1261125	0.1261125	0.0077450	0.0057764	0.9396979
7	IPMHQ	1	72.637327	72.637327	4.4609156	3.3270409	0.0736848
8	LWEB	1	0.1060067	0.1060067	0.0065102	0.0048555	0.9447048
9	RAD1	1	465.73753	465.73753	28.602591	21.332390	2.43e-05
10	SO	1	7.3372648	7.3372648	0.4506074	0.3360721	0.5645163
11	TGD	1	44.769283	44.769283	2.7494403	2.0505881	0.1579106
12	SD	1	568.55104	568.55104	34.916733	26.041605	4.44e-06
13	TWS	1	25.993571	25.993571	1.5963573	1.1905955	0.2800542
14	SOANG	1	1.5899128	1.5899128	0.0976422	0.0728235	0.7882979
15	FILSO	1	28.346603	28.346603	1.7408653	1.2983725	0.2595401
16	Error	54	1178.9502	21.832412	1.3408057	N/A	N/A
17	Total	69	2847.4226	N/A	100.00000	N/A	N/A

[Screening(ANOVA)]

Design of experiment (2) & Fitting

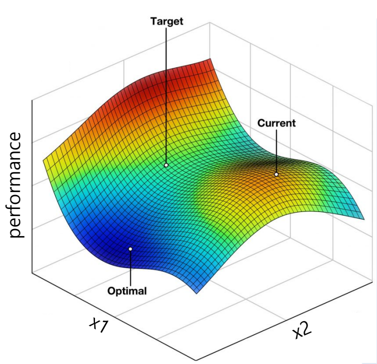


[Fitting(HK)]



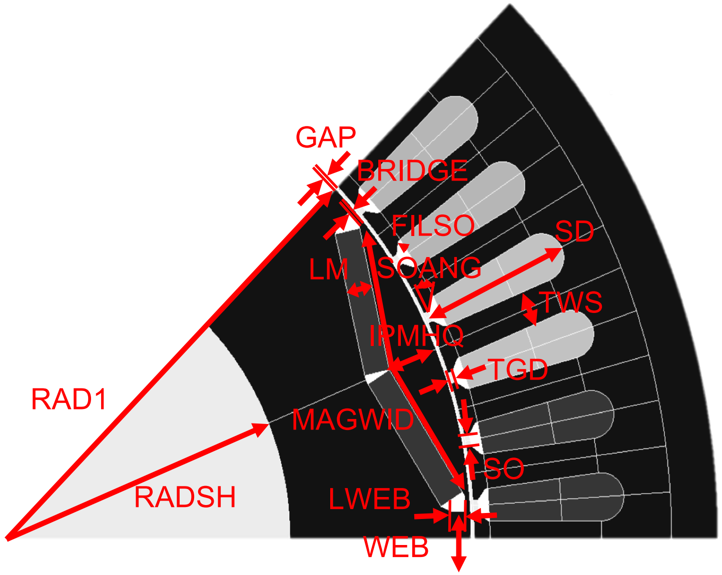
[DoE(LHD)]

Optimization



Formulation

- **Objective function**
  - minimize $w_1 \frac{\Delta T_{\text{cog}}}{T_{\text{cog}}^0} + w_2 \frac{\Delta T_{\text{rip}}}{T_{\text{rip}}^0} + w_3 \frac{\Delta L_{\text{iron}}}{L_{\text{iron}}^0}$
    - w_1, w_2, w_3 : weighted sum
    - T_{cog}^0: Initial cogging torque
    - T_{rip}^0: Initial torque ripple
    - L_{iron}^0: Initial iron losses
- **Design variables**
  - Air gap(GAP)
  - Rotor
    - Shaft radius(RADSH)
    - Thickness of magnet(LM)
    - Web(WEB)
    - Magnet width(MAGWID)
    - Bridge(BRIDGE)
    - Depth of pole cap(IPMHQ)
    - Rad web length(LWEB)
    - Rotor external radius(RAD1)



[Design variables]

- Stator
  - Slot opening(SO)
  - Radial depth(TGD)
  - Slot depth(SD)
  - Tooth width stator(TWS)
  - Slot opening angle(SOANG)
  - Tooth rillet radius near stator slot opening(FILSO)

Formulation

- **Constraint**
  - GAP ≥ 0.6 mm → Airgap
  - BRIDGE ≥ 1 mm
  - $\mathrm{A_{magnet}} \leq A^0_{magnet}$ $(2.7 \cdot 10^{-4}\, m^2)$ → Area of magnet
  - $\mathrm{T_{peak}} \geq T^0_{peak}$ $(400\ \mathrm{N \cdot m})$ → Motor peak torque

^{0} : Initial value

Formulation	
Objective function	minimize $w_1 \dfrac{\Delta T_{\mathrm{cog}}}{T^0_{\mathrm{cog}}} + w_2 \dfrac{\Delta T_{\mathrm{rip}}}{T^0_{\mathrm{rip}}} + w_3 \dfrac{\Delta L_{\mathrm{iron}}}{L^0_{\mathrm{iron}}}$
Design variables	GAP, RADSH, LM, WEB, MAGWID, IPMHQ, LWEB, RAD1, SO, TGD, SD, TWS, SOANG, FILSO
Constraint	GAP ≥ 0.6 mm BRIDGE ≥ 1 mm $\mathrm{A_{magnet}} \leq A^0_{magnet}$ $\mathrm{T_{peak}} \geq T^0_{peak}$

Surrogate model

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- **Surrogate model**
  - Suitable for design that requires a large number of analyses
- **Type**
  - Response surface model(RSM)
    - Smooth modeling, easy to use
    - bad for nonlinear, user need to decide the degree of polynomial
  - Kriging model
    - Good for nonlinear, not sensitive to the value that user should designation
    - Hard to use, same sample make singular correlation matrix
  - Radial basis function(RBF)
    - Good for nonlinear, easy to use
    - Depending on basis function and parameter

HyperStudy

➡ Least squares regression(LSR)

➡ Hyperkriging(HK)

➡ Radial basis function(RBF)

Design of experiment (1)

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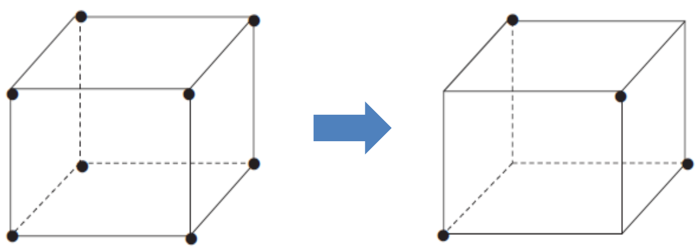
- **Sampling**
  - Fractional factorial design
    - Reduce # of sampling by disregarding negligible high order interaction effect
    - Usually employed for screening experiments
  - Latin hypercube design
    - Every factor should have the same number of levels
    - Used to construct computer experiments

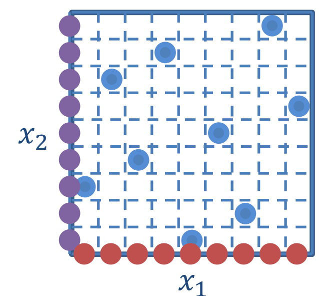
HyperStudy

➡ Fractional factorial(FracFact)

➡ Latin hypercube (LatinHyperCube)



[Fractional factorial design]



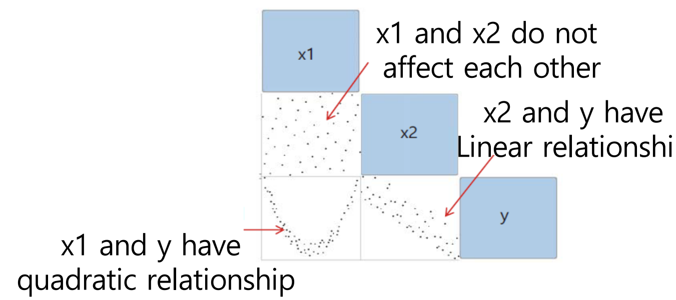
[Latin hypercube design]

- **Design of experiment**
  - Fractional factorial for screening
    - 2 level (32 samples) for linear relationship
    - 3 level (72 samples) for nonlinear relationship
  - Design variables boundary : 10~20%

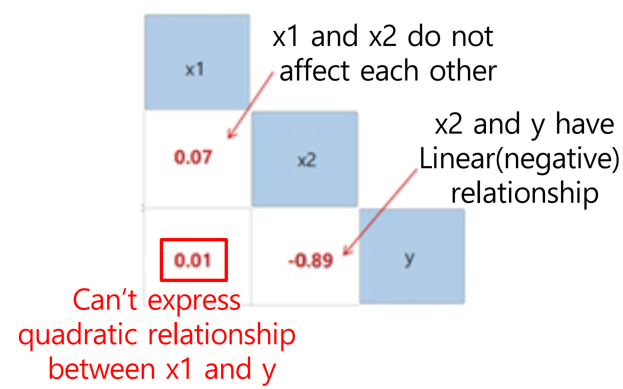
- Response
  - Cogging torque(T_{cog})
  - Torque ripple(T_{rip})
  - Iron losses(L_{iron})

Data analysis & screening

- **Scatter plot**
  - Tool for analyzing the correlation between two factors in 2D plot
  - Not quantitative expression
- **Correlation coefficient**
  - Tool for analyzing the linear correlation between two factors
  - $\rho_{X,Y} = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y}$
- **ANOVA**
  - Determine the relative importance of factors
  - Important factor will have a lower p-value
    - Criterion: 0.05
  - Limited sampling
    - Full factorial design
    - Orthogonal array



[Scatter plot]



[Correlation coefficient]

Data analysis & screening

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- ## ANOVA: cogging torque
  - **3 design** variables are screened

Variables	p-value	Variables	p-value
GAP	0.0693583	**RAD1**	**0.0020965**
RADSH	0.4907868	SO	0.1322403
LM	0.8117471	TGD	0.3892049
WEB	0.3148842	**SD**	**0.0085003**
MAGWID	0.2825898	TWS	0.2745778
BRIDGE	0.6555858	SOANG	0.7696770
IPMHQ	0.6939001	FILSO	0.9050395
LWEB	0.6041003		

[ANOVA_2 level variable]

→

Variables	p-value	Variables	p-value
GAP	0.062413	**RAD1**	**0.000008**
RADSH	0.614291	SO	0.497485
LM	0.06134	TGD	0.16035
WEB	0.989037	**SD**	**0.000002**
MAGWID	**0.001386**	TWS	0.228263
BRIDGE	0.954939	SOANG	0.783999
IPMHQ	0.073173	FILSO	0.267772
LWEB	0.954878		

[ANOVA_3 level variable]

- ## ANOVA: torque ripple
  - **4 design** variables are screened

Variables	p-value	Variables	p-value
GAP	0.1959214	**RAD1**	**0.0029190**
RADSH	0.6230587	SO	0.5529487
LM	0.6969974	TGD	0.8491803
WEB	0.9693832	**SD**	**0.0011000**
MAGWID	0.4503535	TWS	0.3895534
BRIDGE	0.4685878	SOANG	0.7606697
IPMHQ	0.1510469	FILSO	0.7456549
LWEB	0.9358905		

[ANOVA_2 level variable]

→

Variables	p-value	Variables	p-value
GAP	0.2031644	**RAD1**	**0.0000001**
RADSH	0.8579230	SO	0.0808261
LM	0.9505285	TGD	0.0504487
WEB	0.6598610	**SD**	**0.0000000002**
MAGWID	**0.0009200**	TWS	0.1040213
BRIDGE	0.9754715	SOANG	0.6327074
IPMHQ	**0.0192570**	FILSO	0.3282458
LWEB	0.3787603		

[ANOVA_3 level variable]

Data analysis & screening

- ANOVA: iron losses
  - **6 design** variables are screened

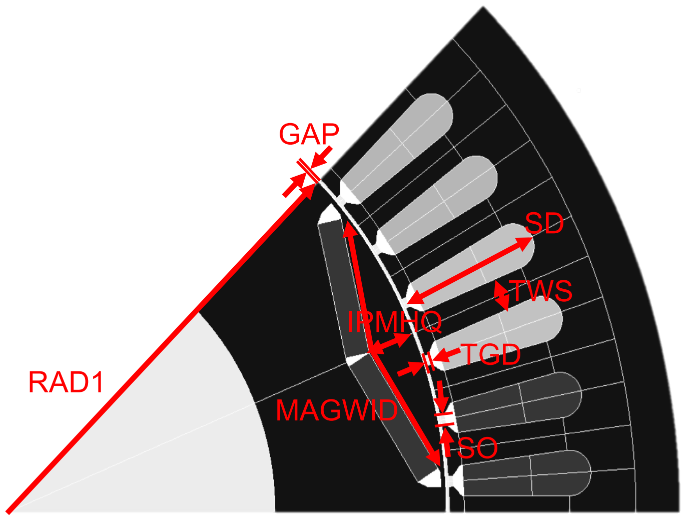
Variables	p-value	Variables	p-value
GAP	**0.0103289**	**RAD1**	**0.000646**
RADSH	0.6825495	SO	0.4273787
LM	0.8572155	TGD	0.9441893
WEB	0.4211522	**SD**	**0.000701**
MAGWID	0.8415521	**TWS**	**0.0045623**
BRIDGE	0.9153773	SOANG	0.7984617
IPMHQ	0.2584207	FILSO	0.9025410
LWEB	0.9534629		

[ANOVA_2 level variable]

Variables	p-value	Variables	p-value
GAP	**0.00000002**	**RAD1**	**2.10E-15**
RADSH	0.9091198	**SO**	**0.0021236**
LM	0.9783552	**TGD**	**0.0170979**
WEB	0.6373757	**SD**	**2.62E-15**
MAGWID	0.7006632	**TWS**	**0.0000008**
BRIDGE	0.5113151	SOANG	0.5634426
IPMHQ	0.2795687	FILSO	0.2714437
LWEB	0.4934220		

[ANOVA_3 level variable]

- ANOVA result
  - **8 design** variables are screened
    - GAP
    - MAGWID
    - IPMHQ
    - RAD1
    - SO
    - TGD
    - SD
    - TWS



[New design variables]

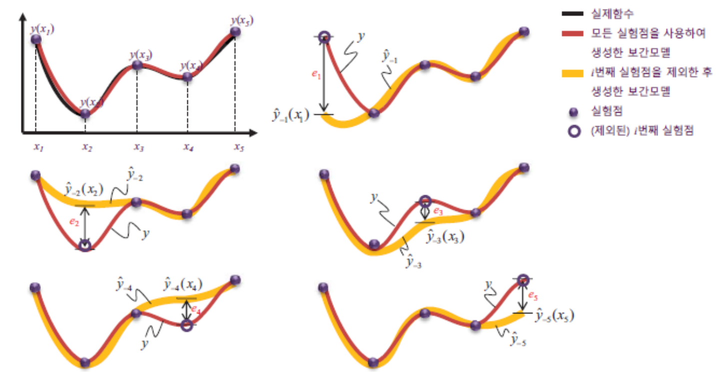
Design of experiment (2) & fitting

- **Design of experiment**
  - Latin hypercube design for fitting
  - Saturated number : $N_{sat} = \frac{(n+1)(n+2)}{2} = 45$
  - Number of sample points: $3N_{sat} = 135$
  - Design variables boundary : 10~20%
  - Response
    - Cogging torque(T_{cog})
    - Torque ripple(T_{rip})
    - Iron losses(L_{iron})
    - Magnet area(A_{magnet})
    - Motor mass(m_{motor})
- **Fitting**
  - Hyperkriging(HK)
  - Radial basis function(RBF)
    - Basis function: Gaussian
    - Parameter: 0.2086

} Choose the best model by validation

Design of experiment (2) & fitting

- **Leave-one-out cross-validation(LOOCV)**
  - Out-of-sample testing for interpolation model
- **Root mean squared error(RMSE)**
  - Good fitting model will have lower RMSE
  - $CV = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_{-i}(\boldsymbol{x}_i) - y(\boldsymbol{x}_i))^2}$



[Diagram of LOOCV]

Selected

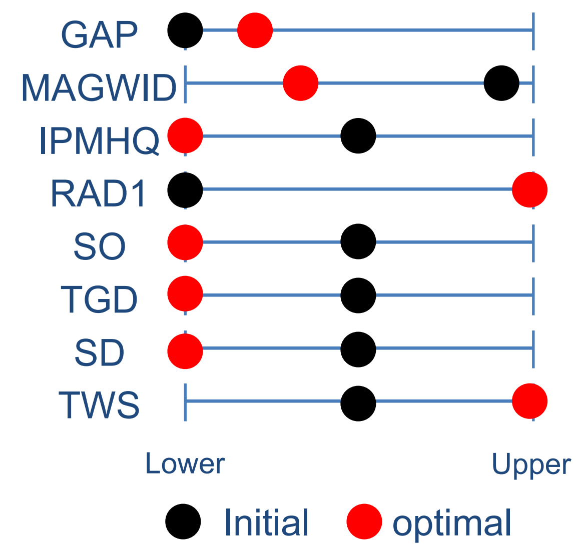
	HK	RBF
Cogging torque	2.4179	4.4457
Torque ripple	5.1373	12.4880
Iron losses	0.6207	2.3938
Magnet area	3.36E-16	1.02E-5
Motor mass	0.0508	1.1008

[LOOCV]

Optimization

- **Optimization method**
  - Adaptive response surface method(ARSM)
    - Maximum iteration: 200
    - Absolute convergence: 0.001
    - Solver: SQP
  - Weight sum: $w_i = 1\ ;\ i = 1\ to\ 3$
- **Design variables result**
  - Round off the numbers to two decimal places for production

	Initial value	Rounded value
GAP	0.77215	0.77
MAGWID	51.20889	51.2
IPMHQ	8.00000	8.0
RAD1	101.00000	101.0
SO	1.60000	1.6
TGD	0.80000	0.8
SD	24.00000	24.0
TWS	7.90000	7.9



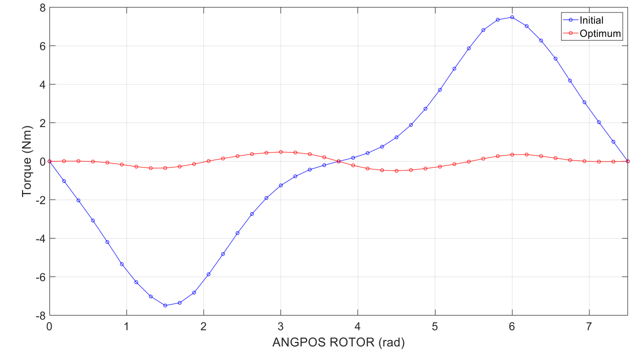
[Design variables]

Optimization

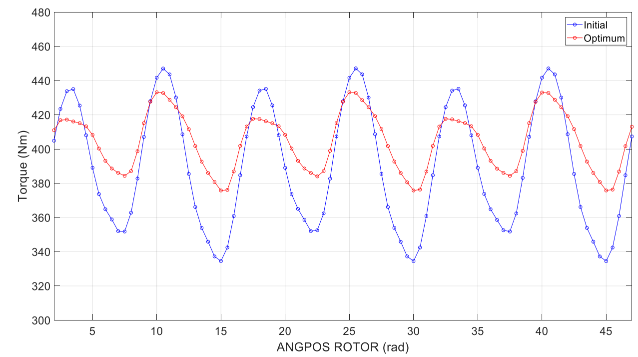
- **Result**
  - Objective

	Initial value	Optimum value
Cogging torque [N · m]	7.4874	0.4879 (93.48% ↓)
Torque ripple [N · m]	112.62	57.43 (49.01% ↓)
Iron losses [W]	22.28	19.41 (12.88% ↓)

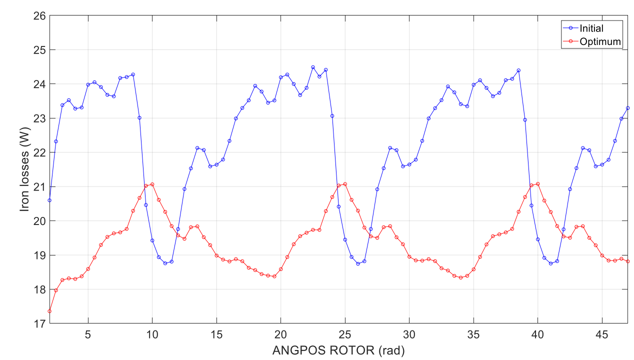
  - Constraint
    - $\mathbf{GAP = 0.77\ mm} > 0.6\ \mathrm{mm}$
    - $\mathbf{BRIDGE = 1\ mm}$
    - $\boldsymbol{A_{magnet} = 2.56 \cdot 10^{-4}\ m^2} < 2.7 \cdot 10^{-4}\ m^2$
    - $\boldsymbol{T_{peak} = 400.96\ \mathrm{N \cdot m}} > 400\ \mathrm{N \cdot m}$ (active)
  - Motor mass: $28.63\ kg < 29.26\ kg$



[Torque at no-current]



[Torque at constant speed(1200rpm)]



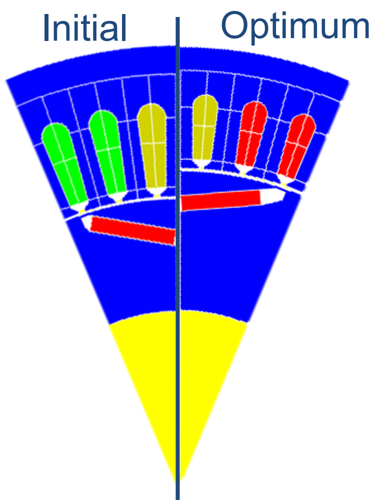
[Iron losses at constant speed(1200rpm)]

Conclusion

Summary

Summary

- Moter modeling and EM analysis by flux and size optimization by hyperstudy
- Using optimization, improve the disadvantage of IPM motor that interrupt hybrid vehicle concept
- There are nonlinear relationship between design variable and response in motor
- Rotor radius(RAD1), and slot length(SD) are important for all responses
- By rounding off the numbers to two decimal places, satisfy production



[Motor shape]

Thank you

Back data

- **Motor production**
  - Stamping

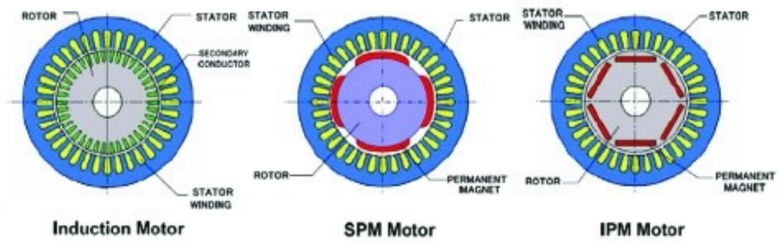
  - Check production by controling value
    - Accuracy : 0.1mm

Back data

[Motor cross section]

Motor background

- **Motor type**
  - Induction motor(IM)
  - Permanent magnet motor
    - Surface permanent magnet(SPM) motor
    - Interior permanent magnet(IPM) motor



[Structures of IM, SPM motor and IPM motor]

Type	SPM motor	IPM motor
Advantage	• At low speed • Low torque ripple • Low cogging torque • Low vibration and noise	• At high speed • Large speed range • High motor torque at same current
Disadvantage	• Small speed range	• High cogging torque • High torque ripple • High vibration and noise

Motor losses

↓

Do improve by optimization

Data analysis & screening

- ## ANOVA: cogging torque
  - **3 design** variables are screened

	Variables	Degrees of Freedom	Sum of Squares	Mean Squares	Mean Squares Percent	F-value	p-value
1	GAP	1	167.53753	167.53753	10.330698	3.9767881	0.0693583
2	RADSH	1	21.285688	21.285688	1.3125180	0.5052520	0.4907868
3	LM	1	2.4974772	2.4974772	0.1539994	0.0592819	0.8117471
4	WEB	1	46.351078	46.351078	2.8581000	1.1002217	0.3148842
5	MAGWID	1	53.318920	53.318920	3.2877510	1.2656153	0.2825898
6	BRIDGE	1	8.8122315	8.8122315	0.5433798	0.2091733	0.6555858
7	IPMHQ	1	6.8485376	6.8485376	0.4222945	0.1625617	0.6939001
8	LWEB	1	11.945894	11.945894	0.7366077	0.2835561	0.6041003
9	RAD1	1	641.95618	641.95618	39.584299	15.237922	0.0020965
10	SO	1	109.90686	109.90686	6.7770763	2.6088263	0.1322403
11	TGD	1	33.626296	33.626296	2.0734645	0.7981773	0.3892049
12	SD	1	415.90326	415.90326	25.645425	9.8721711	0.0085003
13	TWS	1	55.221070	55.221070	3.4050413	1.3107660	0.2745778
14	SOANG	1	3.7791610	3.7791610	0.2330306	0.0897048	0.7696770
15	FILSO	1	0.6254399	0.6254399	0.0385659	0.0148459	0.9050395
16	Error	12	505.54625	42.128854	2.5977492	N/A	N/A
17	Total	27	1942.2930	N/A	100.00000	N/A	N/A

[ANOVA_2 level variable]

	Variables	Degrees of Freedom	Sum of Squares	Mean Squares	Mean Squares Percent	F-value	p-value
1	GAP	1	76.377107	76.377107	4.4907309	3.6149229	0.0624134
2	RADSH	1	5.4265309	5.4265309	0.3190628	0.2568373	0.6142911
3	LM	1	77.028629	77.028629	4.5290384	3.6457594	0.0613404
4	WEB	1	0.0040247	0.0040247	2.37e-04	1.90e-04	0.9890371
5	MAGWID	1	239.27886	239.27886	14.068836	11.325051	0.0013864
6	BRIDGE	1	0.0680667	0.0680667	0.0040021	0.0032216	0.9549391
7	IPMHQ	1	70.452963	70.452963	4.1424102	3.3345336	0.0731726
8	LWEB	1	0.0682510	0.0682510	0.0040129	0.0032303	0.9548782
9	RAD1	1	510.51070	510.51070	30.016406	24.162434	8.10e-06
10	SO	1	9.8532604	9.8532604	0.5793404	0.4663541	0.4974848
11	TGD	1	42.769311	42.769311	2.5146994	2.0242684	0.1603504
12	SD	1	588.37763	588.37763	34.594734	27.847871	2.20e-06
13	TWS	1	31.353567	31.353567	1.8434900	1.4839621	0.2282632
14	SOANG	1	1.6028342	1.6028342	0.0942416	0.0758620	0.7839992
15	FILSO	1	26.472240	26.472240	1.5564835	1.2529292	0.2677720
16	Error	56	1183.1837	21.128281	1.2422757	N/A	N/A
17	Total	71	2862.8277	N/A	100.00000	N/A	N/A

[ANOVA_3 level variable]

- ## ANOVA: torque ripple
  - **5 design** variables are screened

	Variables	Degrees of Freedom	Sum of Squares	Mean Squares	Mean Squares Percent	F-value	p-value
1	GAP	1	0.0512840	0.0512840	5.0439698	1.8215084	0.1959214
2	RADSH	1	0.0070724	0.0070724	0.6955936	0.2511969	0.6230587
3	LM	1	0.0044255	0.0044255	0.4352689	0.1571869	0.6969974
4	WEB	1	4.28e-05	4.28e-05	0.0042090	0.0015200	0.9693832
5	MAGWID	1	0.0168564	0.0168564	1.6578933	0.5987083	0.4503535
6	BRIDGE	1	0.0155189	0.0155189	1.5263394	0.5512008	0.4685878
7	IPMHQ	1	0.0640250	0.0640250	6.2970995	2.2740460	0.1510469
8	LWEB	1	1.88e-04	1.88e-04	0.0184882	0.0066766	0.9358905
9	RAD1	1	0.3463091	0.3463091	34.060797	12.300238	0.0029190
10	SO	1	0.0103429	0.0103429	1.0172662	0.3673612	0.5529487
11	TGD	1	0.0010517	0.0010517	0.1034347	0.0373530	0.8491803
12	SD	1	0.4436731	0.4436731	43.636912	15.758421	0.0011000
13	TWS	1	0.0220238	0.0220238	2.1661245	0.7822438	0.3895534
14	SOANG	1	0.0027031	0.0027031	0.2658649	0.0960107	0.7606697
15	FILSO	1	0.0030667	0.0030667	0.3016217	0.1089234	0.7456549
16	Error	16	0.4504746	0.0281547	2.7691170	N/A	N/A
17	Total	31	1.4390579	N/A	100.00000	N/A	N/A

[ANOVA_2 level variable]

	Variables	Degrees of Freedom	Sum of Squares	Mean Squares	Mean Squares Percent	F-value	p-value
1	GAP	2	0.0193928	0.0096964	1.7859872	1.6573282	0.2031644
2	RADSH	2	0.0017998	9.00e-04	0.1657558	0.1538151	0.8579230
3	LM	2	5.94e-04	2.97e-04	0.0547436	0.0508000	0.9505285
4	WEB	2	0.0049142	0.0024571	0.4525724	0.4199700	0.6598610
5	MAGWID	2	0.0974876	0.0487438	8.9781536	8.3313853	9.20e-04
6	BRIDGE	2	2.91e-04	1.45e-04	0.0267784	0.0248493	0.9754715
7	IPMHQ	2	0.0509714	0.0254857	4.6942314	4.3560683	0.0192570
8	LWEB	2	0.0116335	0.0058167	1.0713888	0.9942081	0.3787603
9	RAD1	2	0.2994993	0.1497496	27.582485	25.595498	6.11e-08
10	SO	2	0.0313160	0.0156580	2.8840581	2.6762963	0.0808261
11	TGD	2	0.0376236	0.0188118	3.4649541	3.2153457	0.0504487
12	SD	2	0.4717956	0.2358978	43.450177	40.320113	2.08e-10
13	TWS	2	0.0279989	0.0139994	2.5785652	2.3928105	0.1040213
14	SOANG	2	0.0054165	0.0027082	0.4988307	0.4628960	0.6327074
15	FILSO	2	0.0133958	0.0066979	1.2336887	1.1448162	0.3282458
16	Error	41	0.2398756	0.0058506	1.0776303	N/A	N/A
17	Total	71	1.3140057	N/A	100.00000	N/A	N/A

[ANOVA_3 level variable]

Data analysis & screening

- ## ANOVA: iron losses
  - **6 design** variables are screened

	Variables	Degrees of Freedom	Sum of Squares	Mean Squares	Mean Squares Percent	F-value	p-value
1	GAP	1	30.086261	30.086261	14.374661	8.4401838	0.0103289
2	RADSH	1	0.6184847	0.6184847	0.2955006	0.1735053	0.6825495
3	LM	1	0.1191758	0.1191758	0.0569400	0.0334327	0.8572155
4	WEB	1	2.4299199	2.4299199	1.1609709	0.6816723	0.4211522
5	MAGWID	1	0.1471629	0.1471629	0.0703117	0.0412840	0.8415521
6	BRIDGE	1	0.0415397	0.0415397	0.0198469	0.0116532	0.9153773
7	IPMHQ	1	4.8949007	4.8949007	2.3386933	1.3731803	0.2584207
8	LWEB	1	0.0125267	0.0125267	0.0059850	0.0035142	0.9534629
9	RAD1	1	63.585831	63.585831	30.380138	17.837913	6.46e-04
10	SO	1	2.3641653	2.3641653	1.1295546	0.6632260	0.4273787
11	TGD	1	0.0180265	0.0180265	0.0086127	0.0050570	0.9441893
12	SD	1	62.409334	62.409334	29.818029	17.507867	7.01e-04
13	TWS	1	38.713239	38.713239	18.496472	10.860334	0.0045623
14	SOANG	1	0.2402814	0.2402814	0.1148020	0.0674068	0.7984617
15	FILSO	1	0.0551723	0.0551723	0.0263603	0.0154776	0.9025410
16	Error	16	57.034323	3.5646452	1.7031218	N/A	N/A
17	Total	31	262.77034	N/A	100.00000	N/A	N/A

[ANOVA_2 level variable]

	Variables	Degrees of Freedom	Sum of Squares	Mean Squares	Mean Squares Percent	F-value	p-value
1	GAP	2	46.433061	23.216530	11.843290	28.130169	2.04e-08
2	RADSH	2	0.1576373	0.0788187	0.0402072	0.0955002	0.9091198
3	LM	2	0.0361397	0.0180698	0.0092178	0.0218942	0.9783552
4	WEB	2	0.7516733	0.3758366	0.1917230	0.4553802	0.6373757
5	MAGWID	2	0.5923064	0.2961532	0.1510746	0.3588322	0.7006632
6	BRIDGE	2	1.1255185	0.5627592	0.2870765	0.6818638	0.5113151
7	IPMHQ	2	2.1705383	1.0852692	0.5536209	1.3149598	0.2795687
8	LWEB	2	1.1863251	0.5931625	0.3025860	0.7187018	0.4934220
9	RAD1	2	142.10526	71.052629	36.245592	86.090490	2.10e-15
10	SO	2	11.849016	5.9245082	3.0222289	7.1783947	0.0021236
11	TGD	2	7.4290465	3.7145233	1.8948643	4.5006797	0.0170979
12	SD	2	140.23254	70.116271	35.767933	84.955956	2.62e-15
13	TWS	2	33.159755	16.579878	8.4577796	20.088909	8.29e-07
14	SOANG	2	0.9603359	0.4801679	0.2449448	0.5817926	0.5634426
15	FILSO	2	2.2223815	1.1111907	0.5668441	1.3463676	0.2714437
16	Error	41	33.838323	0.8253250	0.4210174	N/A	N/A
17	Total	71	424.24986	N/A	100.00000	N/A	N/A

[ANOVA_3 level variable]