

# IPMSMの弱め磁束制御による最適なトルク制御の キャリブレーション

MathWorks Japan  
アプリケーションエンジニアリング部



# はじめに

## 本セミナーの対象者

- モーター制御開発者
- モーター適合エンジニア

## 本セッションでお伝えしたいこと

**Model-Based Calibration Toolboxを活用した  
モーターのトルク制御マップのキャリブレーション方法**

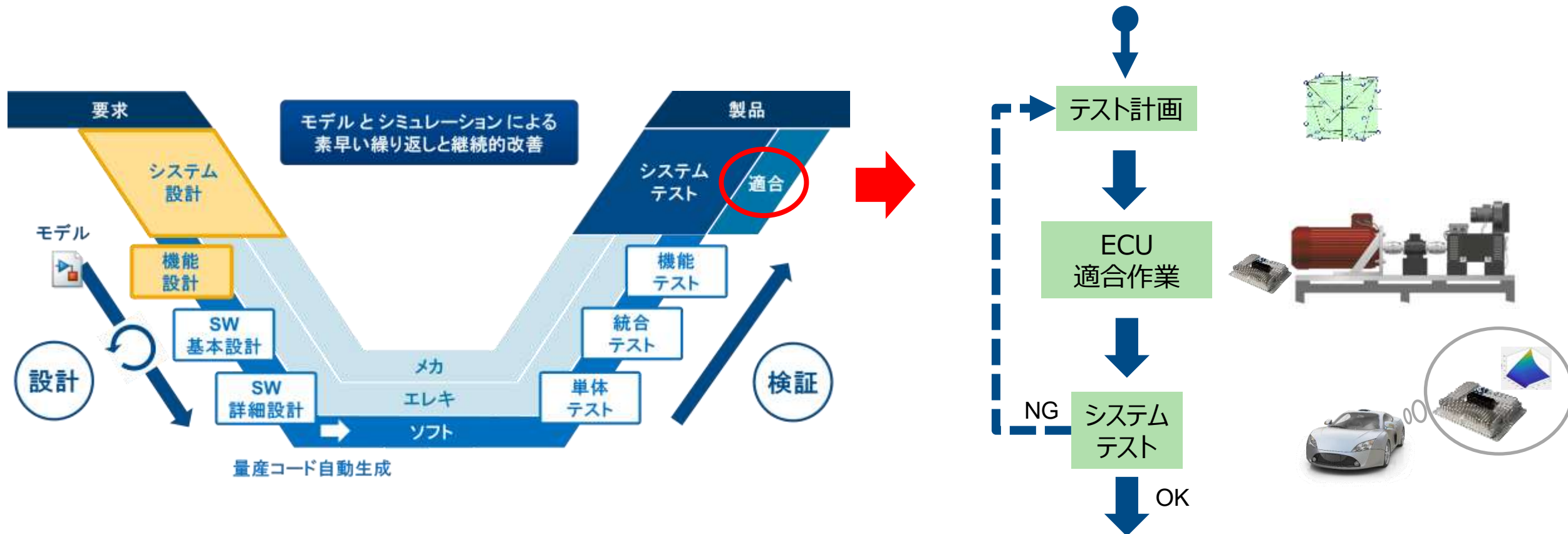
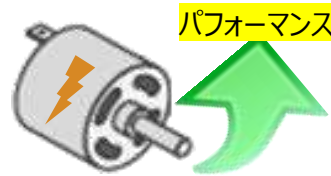
# モーターを使用した様々な電動機器



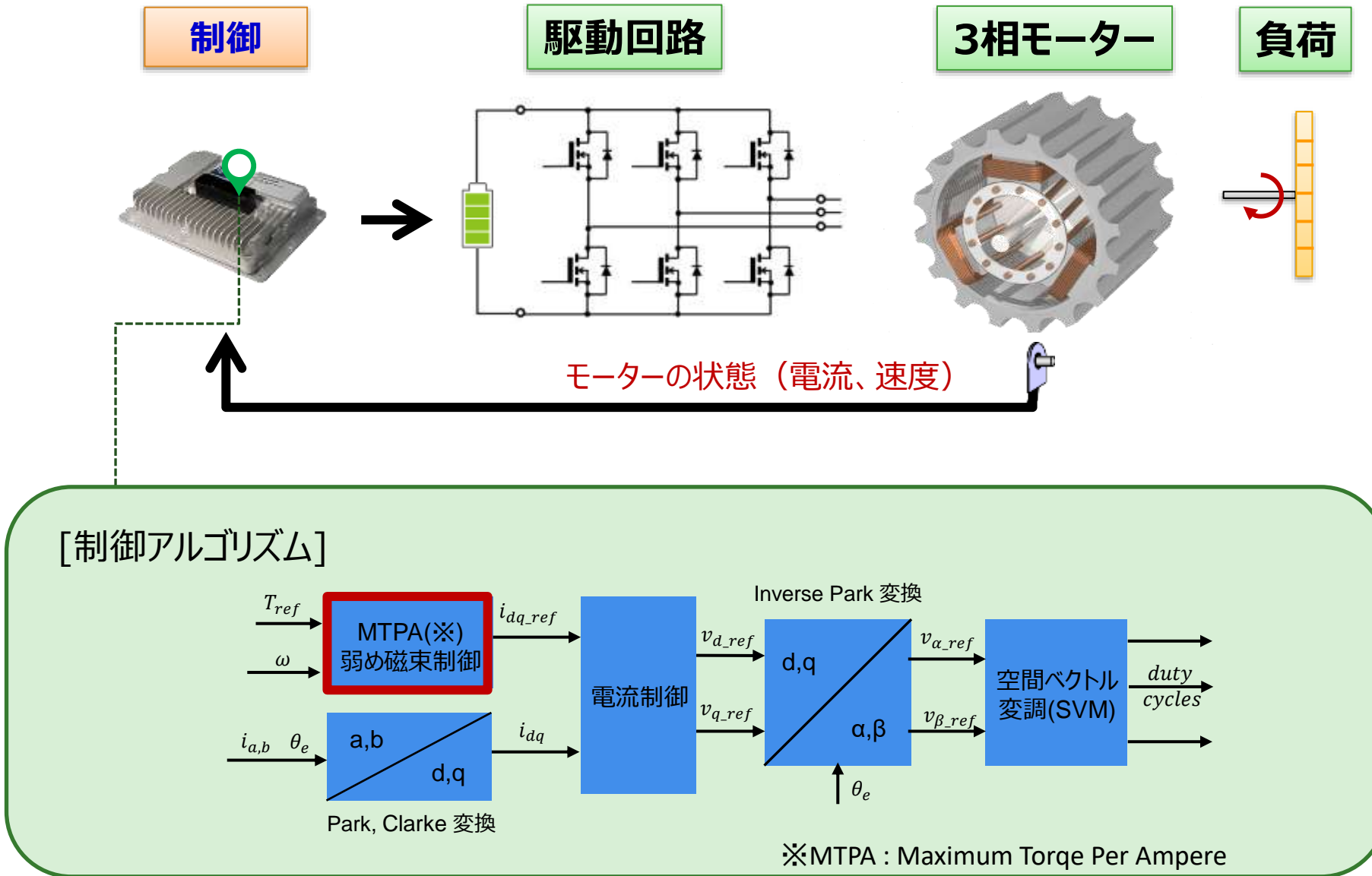
# キャリブレーション(適合)とは

要求性能に対して、制御パラメータを最適化すること。

⇒ モーターの要求出力を満たすために、制御パラメータが最適値になるよう調整



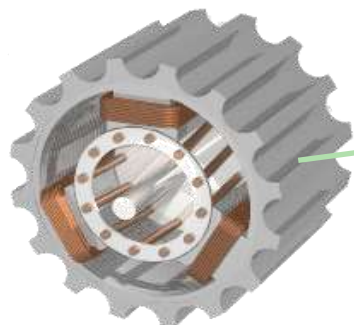
# モーターシステムの構成







# 弱め磁束制御とは？



d-q座標軸上で表現したPMSMの電圧方程式

$$v_d = R_s i_d + \frac{d\lambda_d}{dt} - \omega_e L_q i_q$$

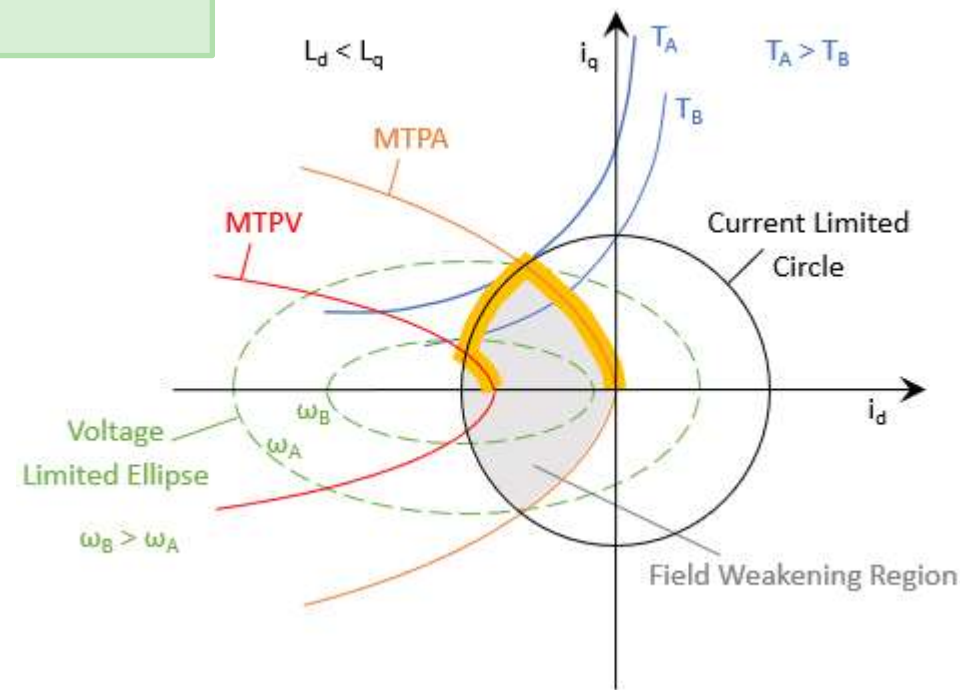
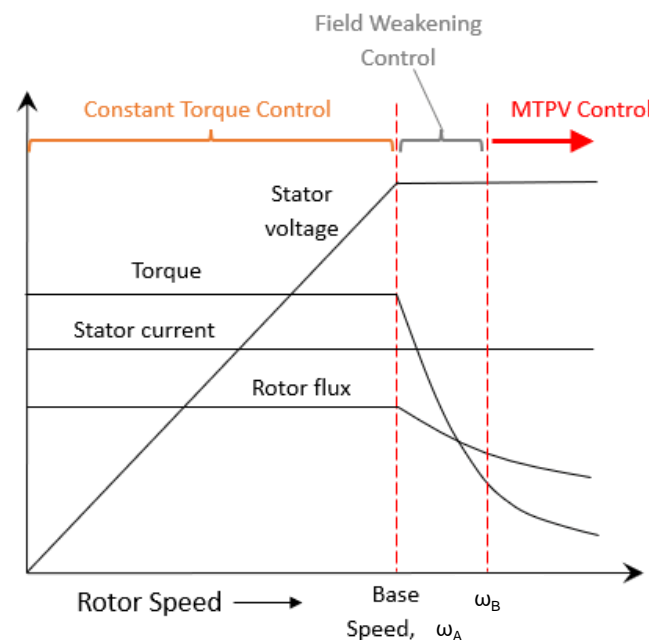
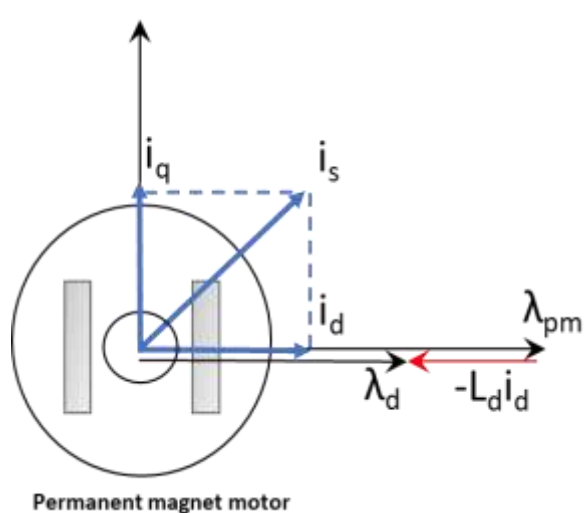
$$v_q = R_s i_q + \frac{d\lambda_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_{pm}$$

$$\lambda_d = L_d i_d + \lambda_{pm} \quad \lambda_q = L_q i_q$$

トルク式

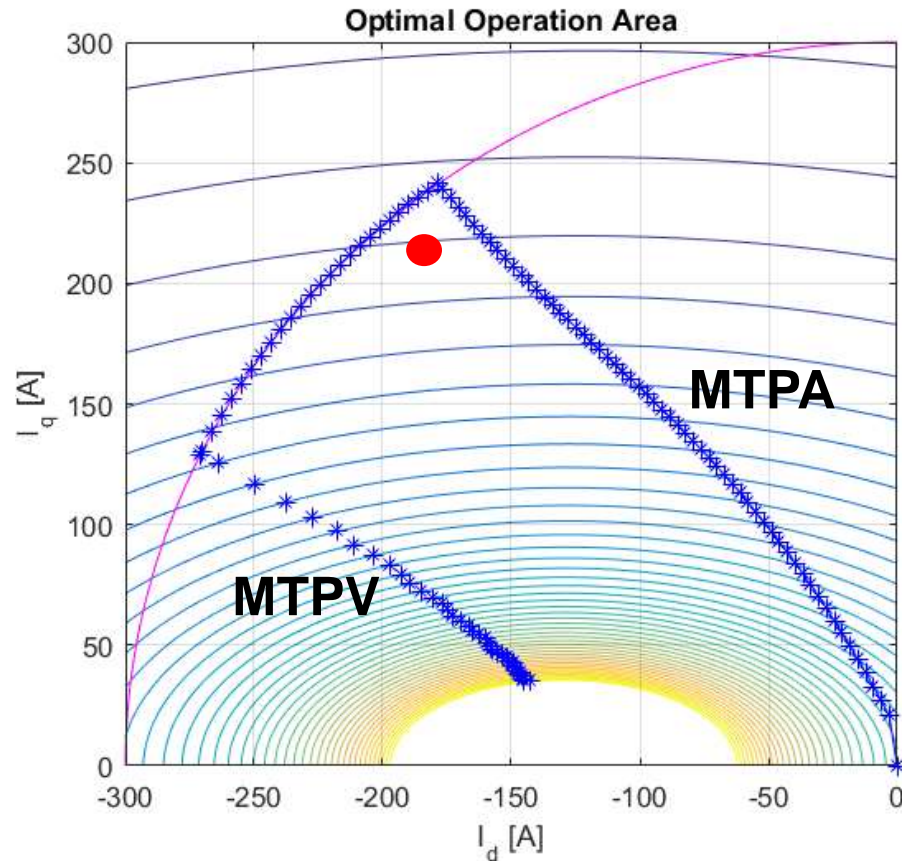
$$T = 1.5p[\lambda_{pm} i_q + (L_d - L_q) i_d i_q]$$

$v_d, v_q$ : 電気子電圧の $d, q$ 軸成分  
 $L_d$ :  $d$ 軸インダクタンス  
 $L_q$ :  $q$ 軸インダクタンス  
 $R_s$ : 電気子巻線抵抗  
 $i_d, i_q$ : 電気子電流の $d, q$ 軸成分  
 $\omega_e$ : 電気角速度  
 $\lambda_{pm}$ : 永久磁石の鎖交磁束  
 $\lambda_d \lambda_q$ : 鎖交磁束の $d, q$ 軸成分  
 $p$ : 極対数

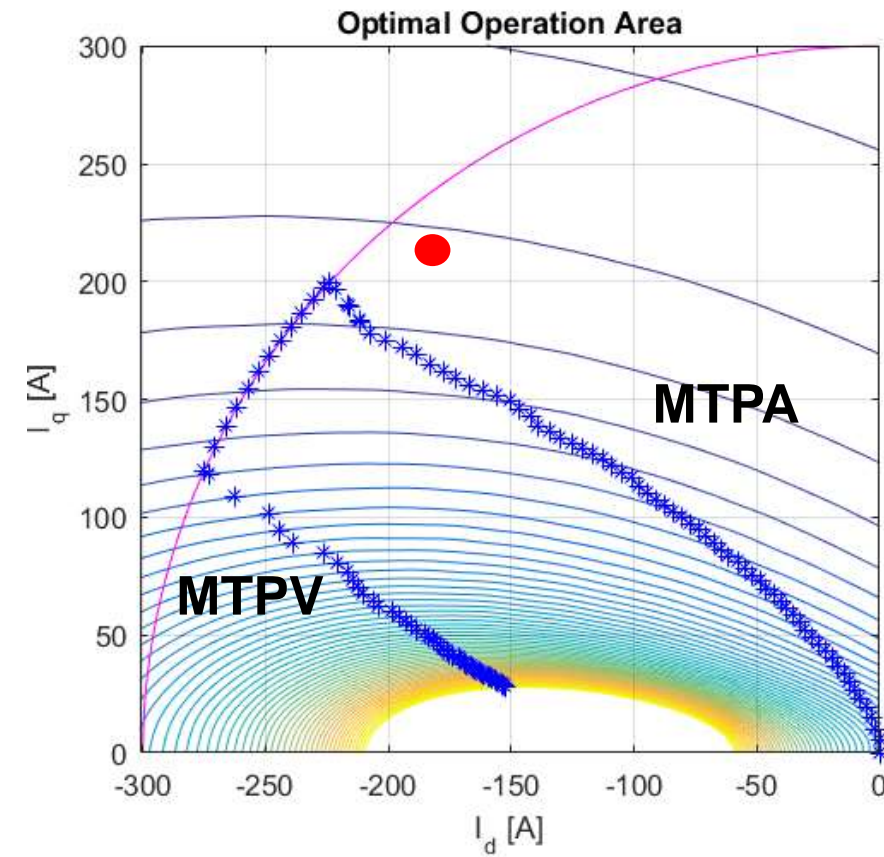


IPMSMの動作領域図

## 弱め磁束制御における飽和の影響



線形モデル

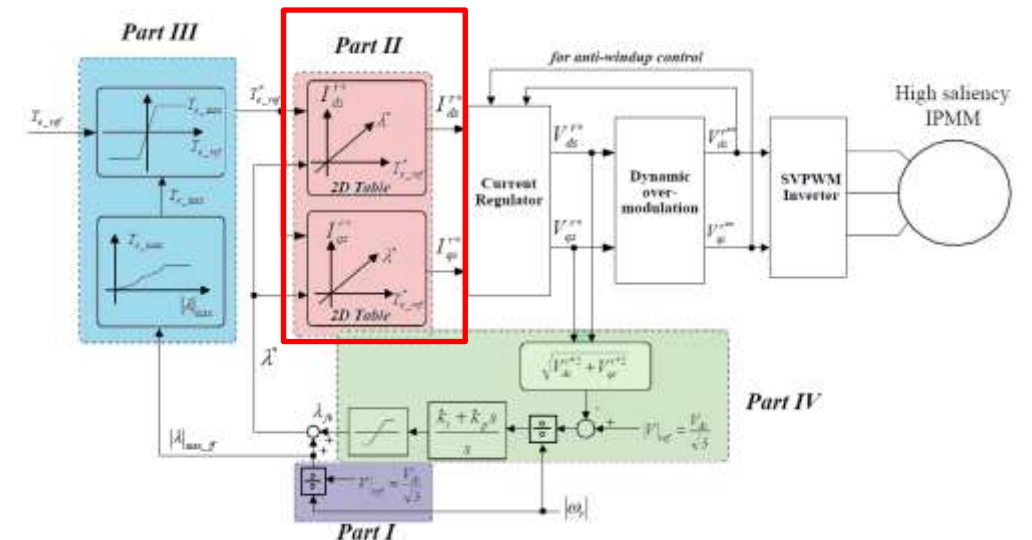
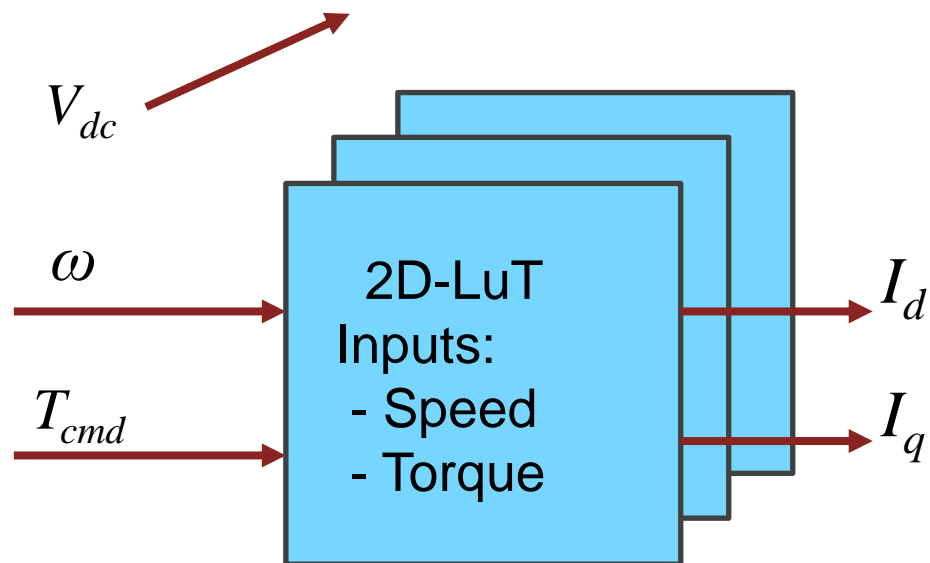


ダイナモテストによる軌跡

線形IPMSMのパラメータから計算される最適な弱め磁束点は、磁気飽和により実際のモータに適用できない場合があります。

# 弱め磁束制御のルックアップテーブル アルゴリズム

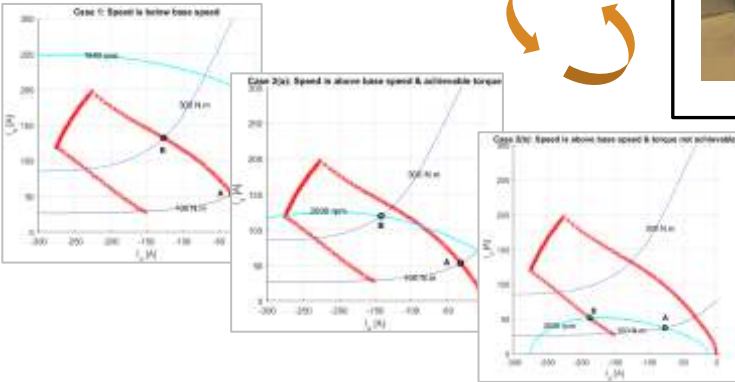

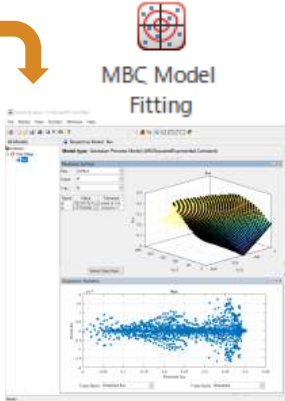
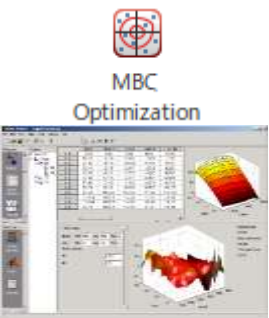
- 速度ベースのトルク制御テーブル
- 最大磁束ベースのトルク制御テーブル



Reference: Bon-Ho Bae, Patel N., Schulz, S., Seung-Ki Sul, "New Field Weakening Technique for High Saliency Interior Permanent Magnet Motor" 38th IAS Annual Meeting. Conference Record of the Industry Applications Conference, Vol. 2, pp.898-905, 2003.



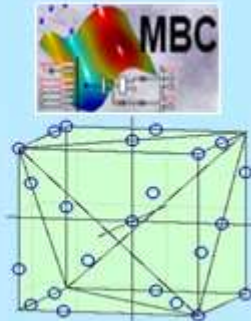
# キャリブレーションの手法

アプローチ方法	ルールベース手法(従来)	モデルベース手法(MBC)
概要	<p>テストベンチ上で、手動にて最適点を探索する手法</p> 	<p>複雑な非線形システムをモデル化してキャリブレーションするための手法</p>   
時間とコスト	ベンチのリソースとエンジニアが拘束され時間がかかる	データ収集後は、オフラインで処理するので、エンジニアの時間を節約し、プロジェクトを合理的に進めることができる
キャリブレーションの質	エンジニアの経験値に左右される	品質が保証され、技術者の未熟さに影響されない

# Model-Based Calibration (MBC) のワークフロー

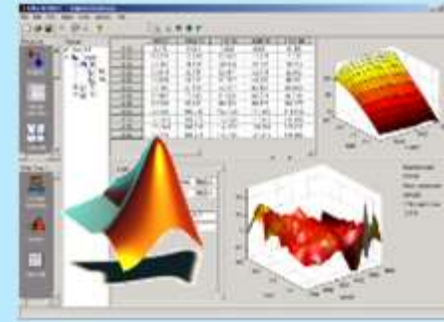
## テスト計画

操作点の設計  
計測器  
インターフェース  
DoE



## キャリブレーション

目的関数の設定  
制約条件の設定  
最適化

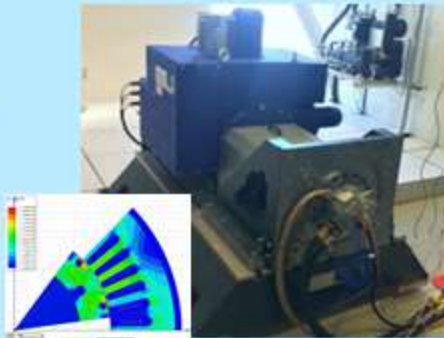


## 実装



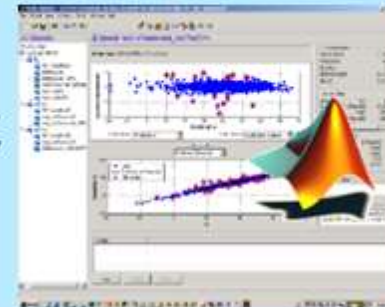
## テスト実施

操作点の設定  
実機準備  
データ計測



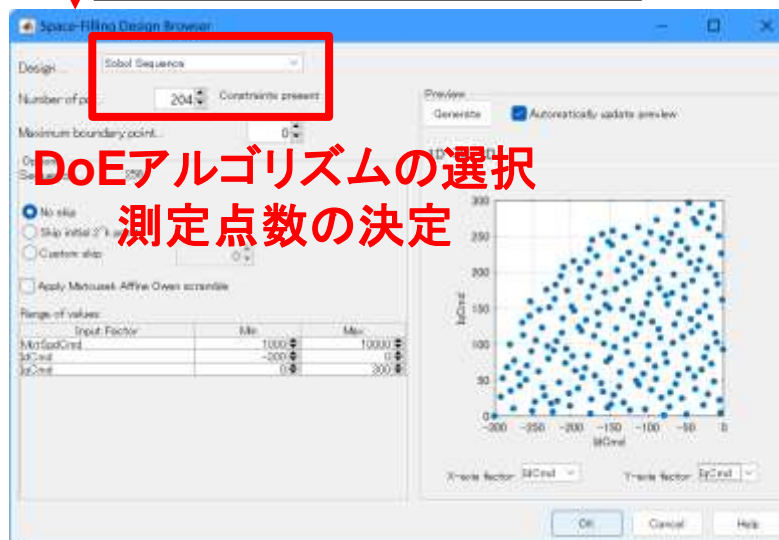
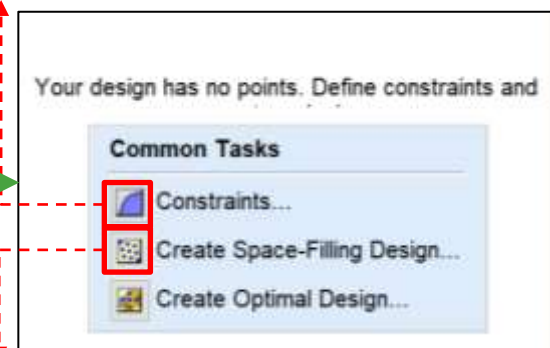
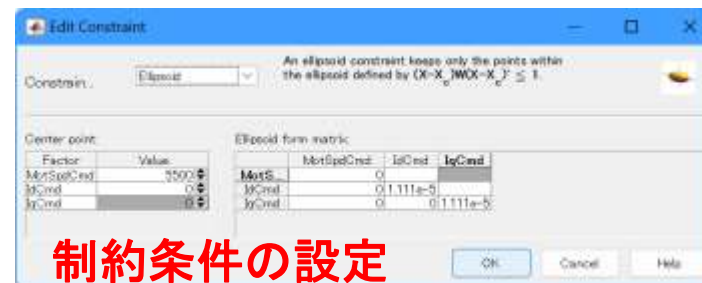
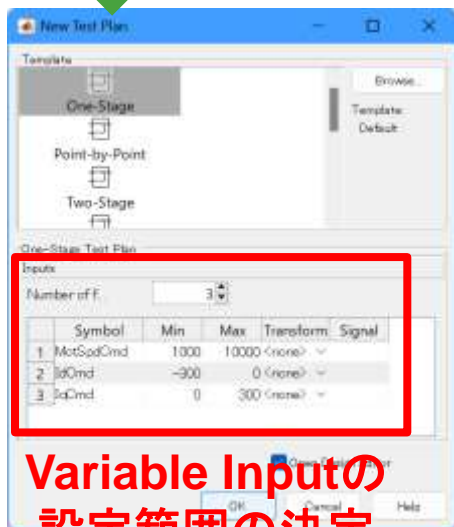
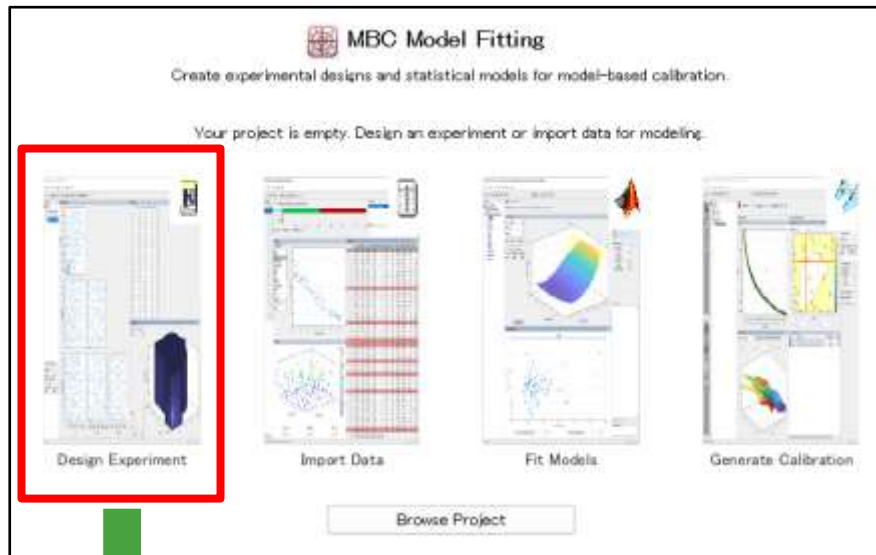
## モデリング

データ前処理  
統計モデル作成





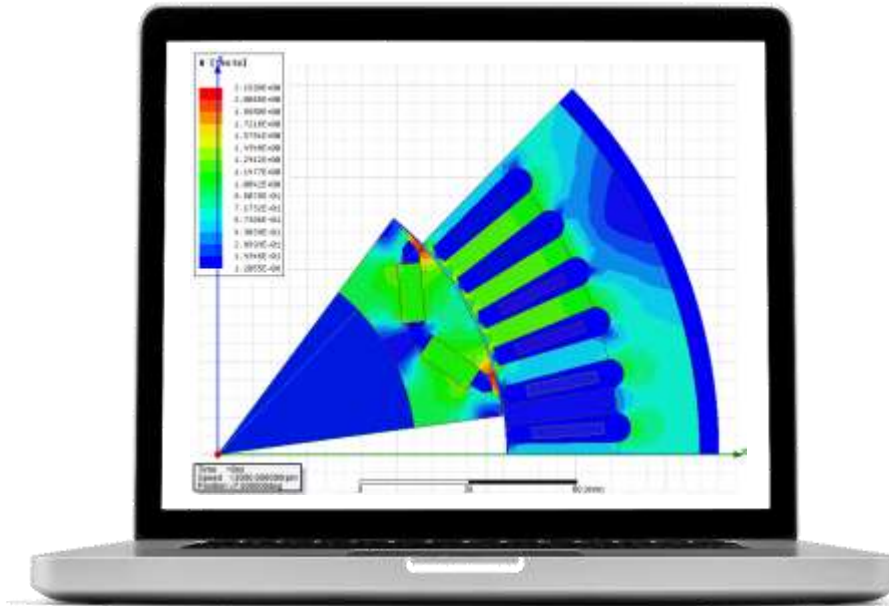
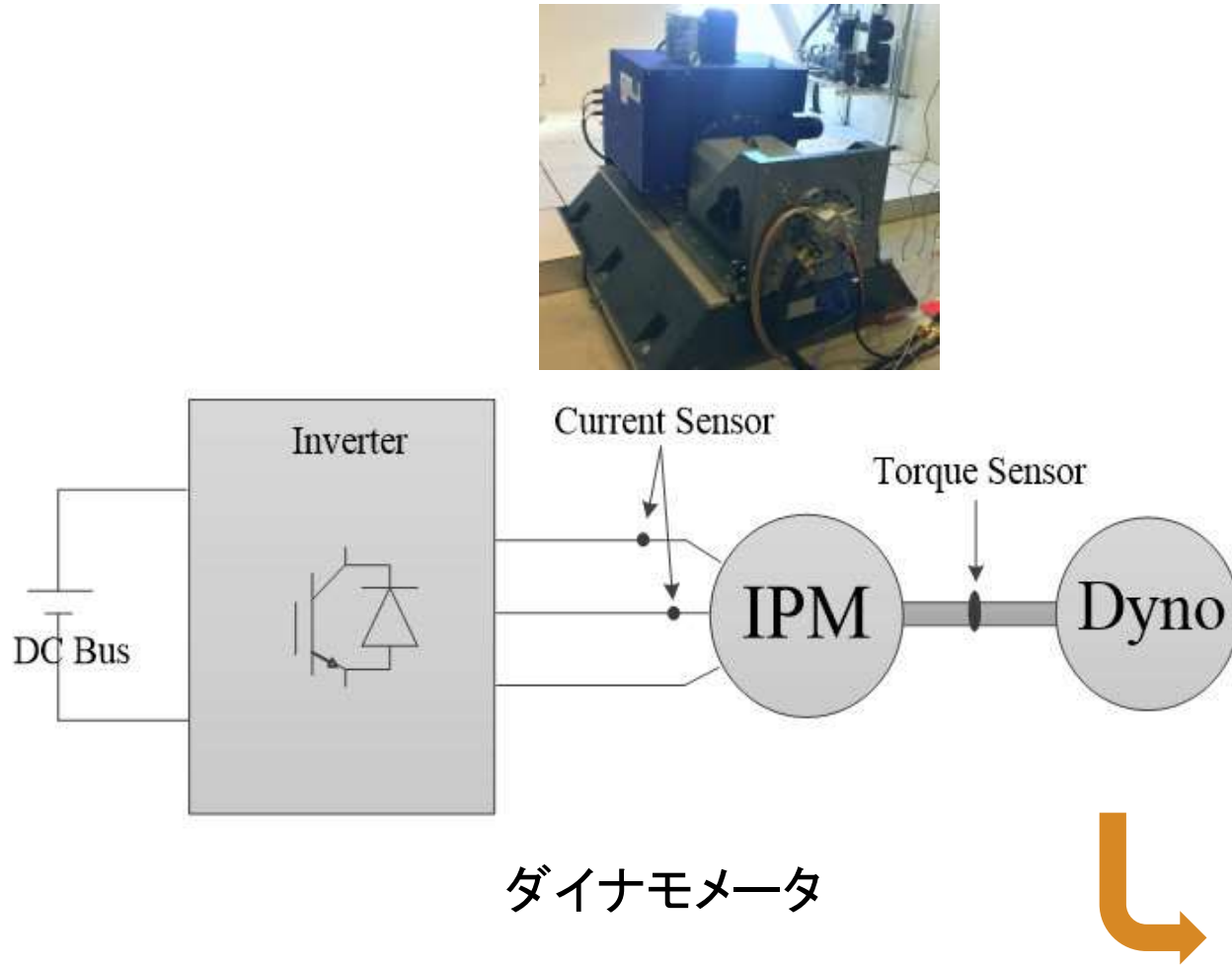
# テスト計画 : DoE試験計画



	MotSpdCmd	IdCmd	IqCmd
1	1000	-300	0
2	5500	-150	150
3	3250	-75	75
4	2125	-112.5	262.5
5	6625	-262.5	112.5
6	4375	-187.5	187.5
7	8875	-37.5	37.5
8	1562.5	-18.75	206.25
9	6062.5	-168.75	56.25
10	8312.5	-93.75	131.25
11	2687.5	-206.25	93.75
12	7187.5	-56.25	243.75
13	4937.5	-131.25	18.75
14	1281.25	-140.625	121.875
15	3531.25	-215.625	46.875
16	8031.25	-65.625	196.875
17	2406.25	-253.125	159.375
18	6906.25	-103.125	9.375
19	4656.25	-28.125	234.375
20	9156.25	-178.125	84.375
21	1843.75	-159.375	253.125
22	6343.75	-9.375	103.125
23	4093.75	-84.375	178.125
24	8593.75	-234.375	28.125
25	2968.75	-46.875	65.625
26	7468.75	-196.875	215.625
27	1140.625	-60.938	285.938
28	5640.625	-210.938	135.938
29	7890.625	-135.938	60.938
30	2265.625	-173.438	23.438
31	6765.625	-23.438	173.438
32	4515.625	-98.438	98.438
33	1300.125	-200.000	70.000



# テスト実施: データ採取 (PMSM の特性評価)



FEA

ログデータ

Time	Current (A)	Torque (Nm)	Speed (rpm)	Power (W)
0.000	0.000	0.000	0.000	0.000
0.001	0.001	0.001	0.001	0.001
0.002	0.002	0.002	0.002	0.002
0.003	0.003	0.003	0.003	0.003
0.004	0.004	0.004	0.004	0.004
0.005	0.005	0.005	0.005	0.005
0.006	0.006	0.006	0.006	0.006
0.007	0.007	0.007	0.007	0.007
0.008	0.008	0.008	0.008	0.008
0.009	0.009	0.009	0.009	0.009
0.010	0.010	0.010	0.010	0.010

Reference: D. Hu, "Designing a Torque Controller for a PMSM through Simulation on a Virtual Dynamometer", MathWorks technical article.

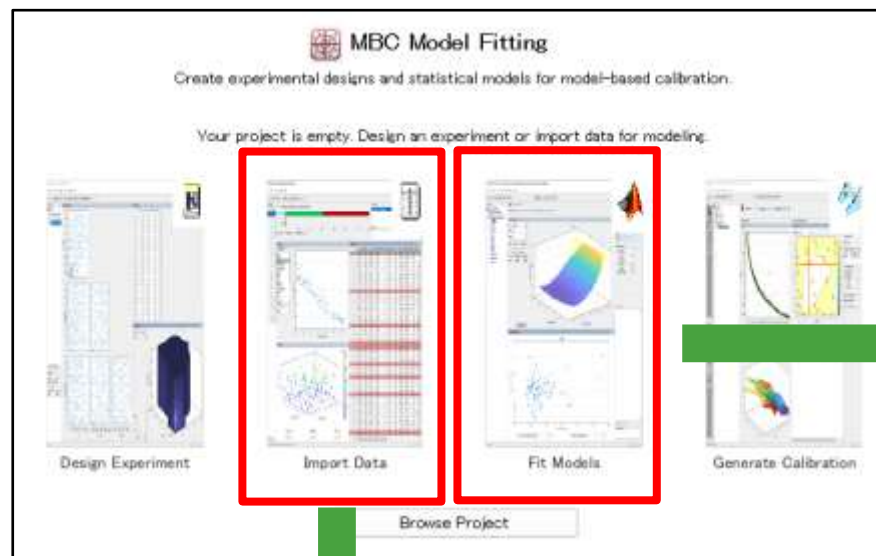
<https://www.mathworks.com/company/newsletters/articles/designing-a-torque-controller-for-a-pmsm-through-simulation-on-a-virtual-dynamometer.html>



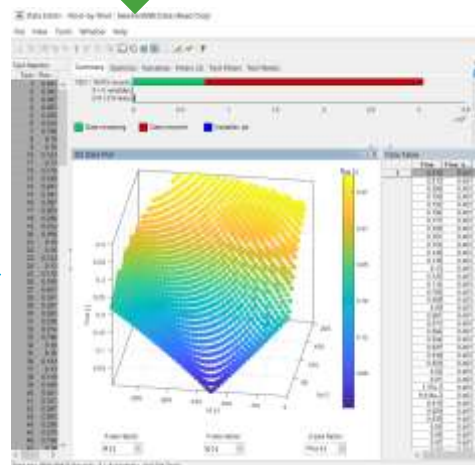




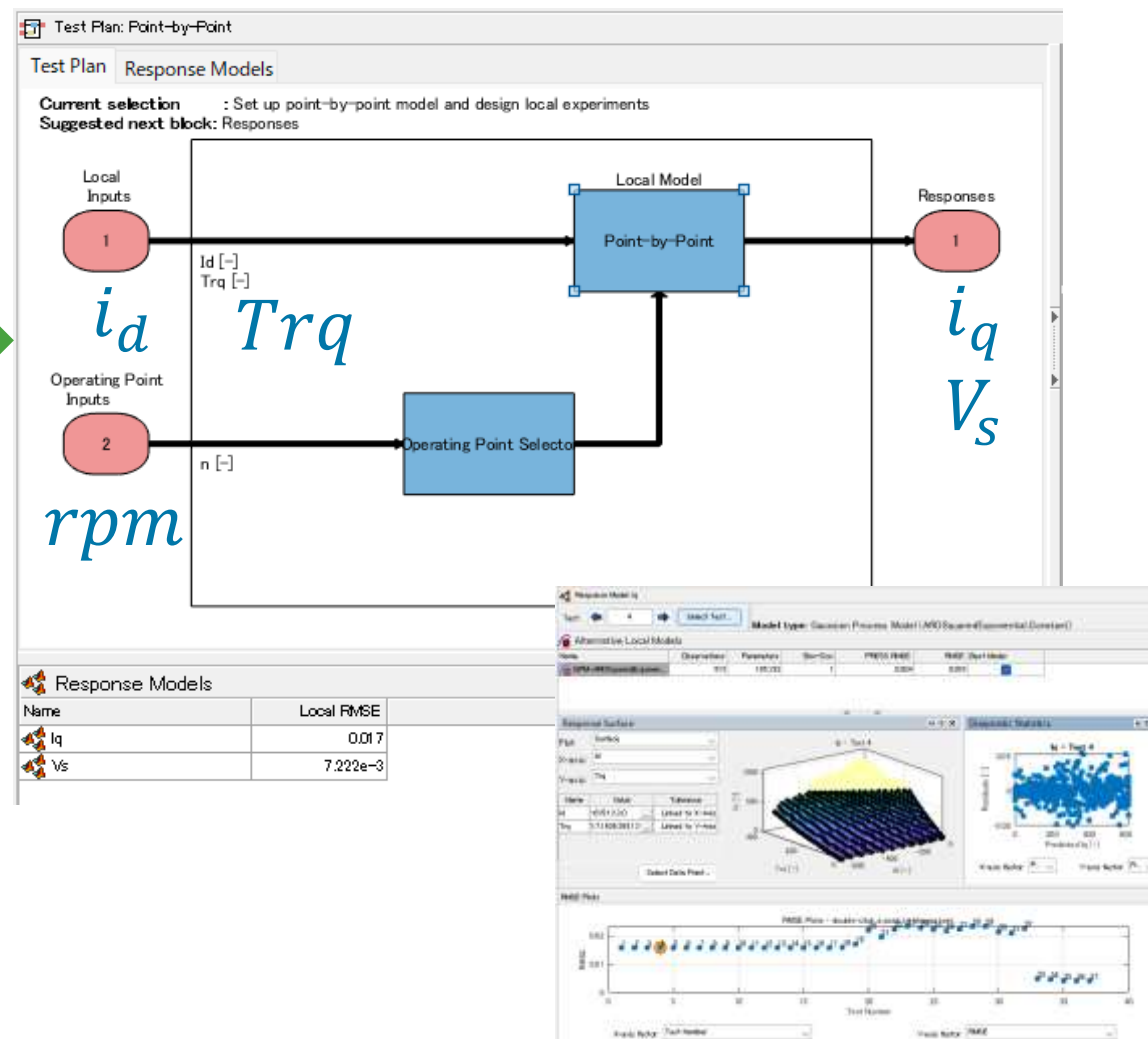
# モデリング:統計モデルの作成



①



②





# キャリブレーション

作成したモデルを使用し、物理的制約を満たしながら、設定した最適化目標を達成できる( $I_d, I_q$ )動作点を探索する

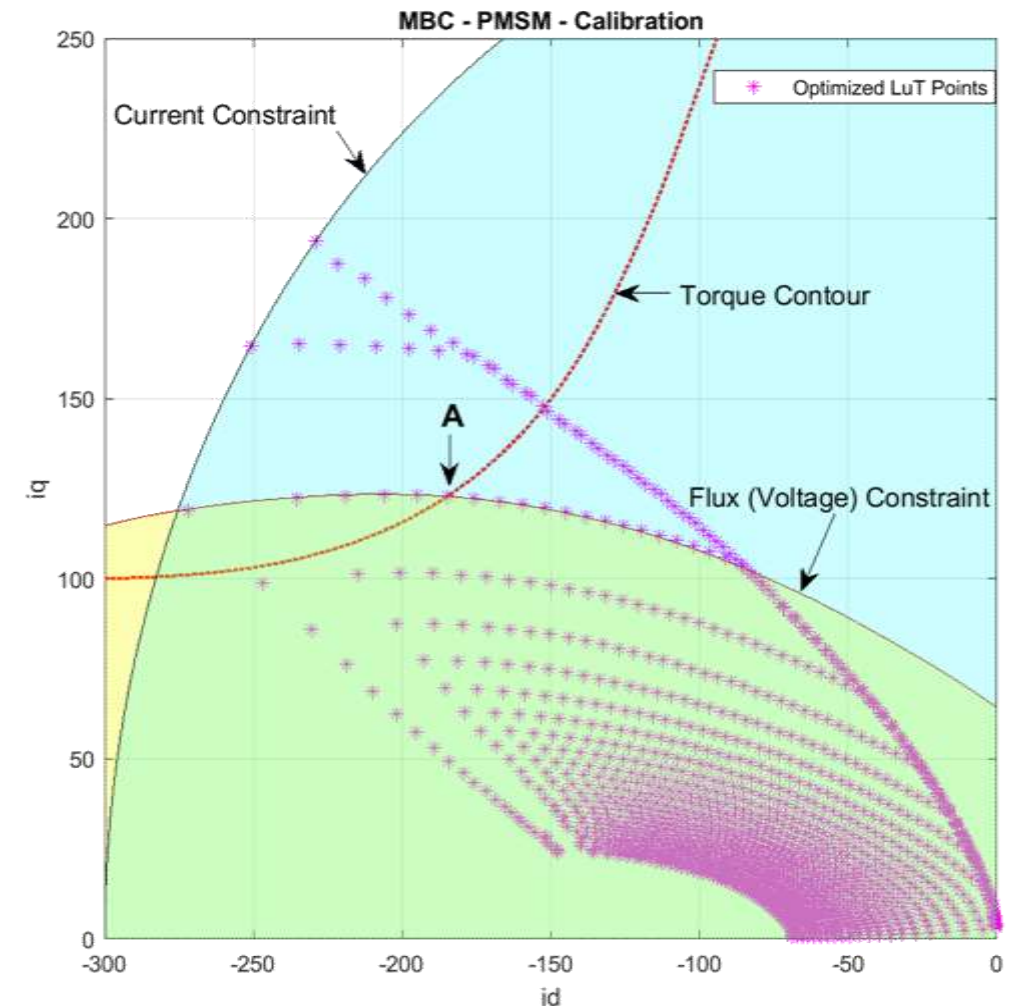
< 目的関数 >

$$\begin{aligned} \text{MTPA} &= \max \left( \frac{\text{Torque}}{I_s} \right) \\ &= \max f(I_d, I_q) \end{aligned}$$

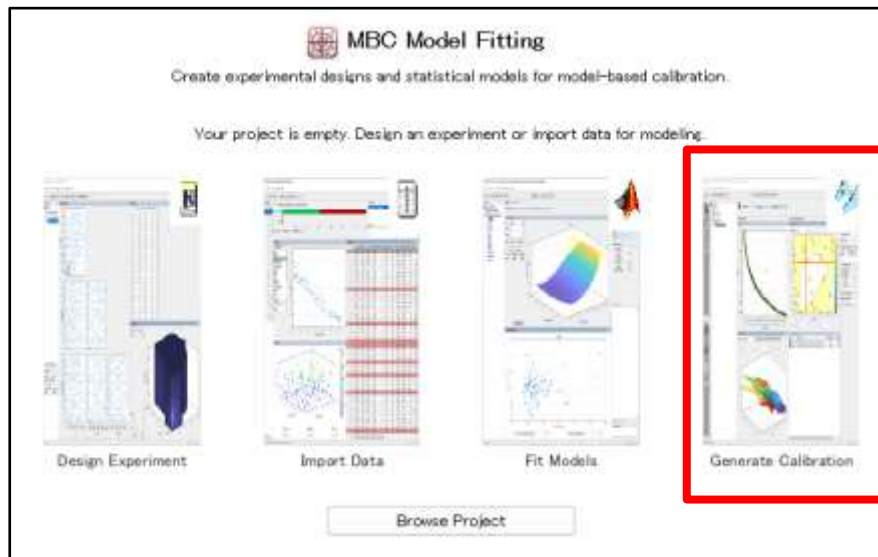
<制約条件>

$$I_s(I_d, I_q) \leq I_s \max$$

$$V_s(I_d, I_q, n, \text{trq}) \leq V_s \max$$



# キャリブレーション



**Create Optimization**

Choose optimization type and select free variables to optimize.

**アルゴリズム選択**

Algorithm: fmincon  
Object: Point  
Data source: ga  
Free variables: 3 selected

**CAGE Browser**

File Edit Optimization Tools Window Help

**Processes**

- Feature Filling
- Tradeoffs
- Optimization
- Data Objects

**Optimization**

- Untitled
- TrqPotOptimization
- TPAOptimization

**Objectives**

Name	Description
TPA	TPA(d, n, TrqPotInput)

**目的関数**

**Constraints**

Name	Description
TPA_Boundary	Boundary constraint of TPA(d, n, TrqPotInput)
Ys	Ys(d, n, TrqPotInput) <= 222.8
Is	Is(d, n, TrqPotInput) <= 615
Iq_Boundary	Boundary constraint of Iq(d, n, TrqPotInput)

**制約条件**

**Optimization Point Set**

Number of operating points: 962

**Free Variables**

Variable	Id
1	-307.5
2	-307.5
3	-307.5
4	-307.5
5	-307.5
6	-307.5
7	-307.5

**Fixed Variables**

Variable	Id
1	-307.5
2	-307.5
3	-307.5
4	-307.5
5	-307.5
6	-307.5
7	-307.5

**Common Tasks**

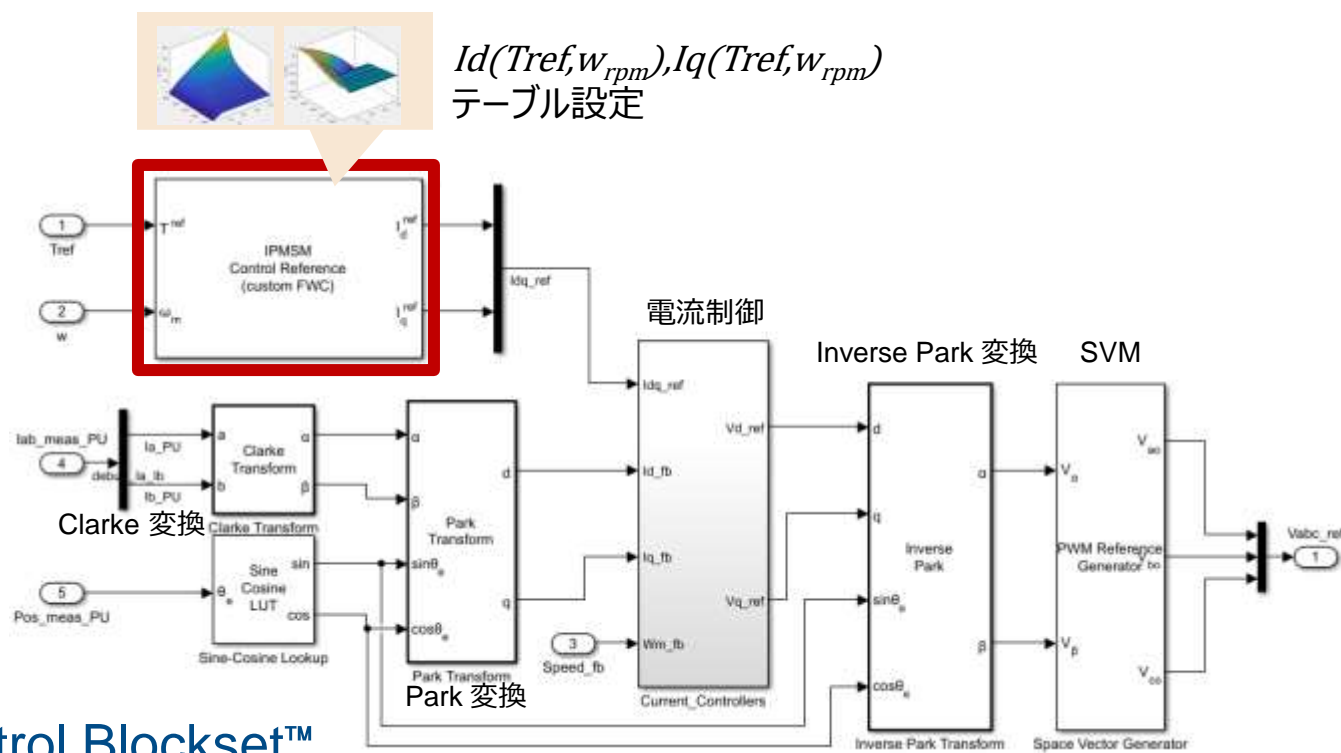
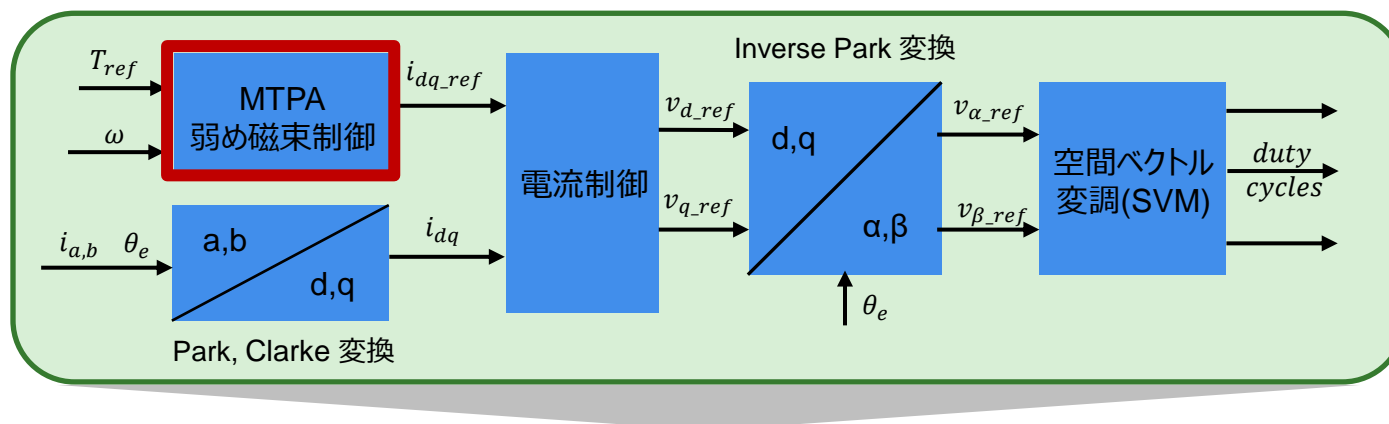
- Add Constraint...
- Set Up
- Run...**
- View Results

**Optimization Progress - TPA, Optimization**

Optimize point 962. Completed 964/962. (964 successful)



## 実装



# User Story



## Model-Based Calibration For Automotive Traction Motors

Daniel Berry

Technical Specialist – Electric Drive Integration  
May 5, 2021

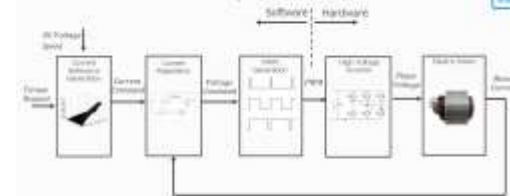
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### Motivation For MBC

- With 30 new electric vehicles planned to launch globally by 2025, General Motors is continually looking for ways to improve and optimize the process it uses for calibration of electric drive systems
  - Improved speed both in required calibration time and in data processing
  - A scalable and standardized workflow
  - Improved data quality checks to ensure first time quality



### Electric Drive Control System Overview



### Advantages of Model-Based Calibration Toolbox

- Speed
  - Full table generation can be done in 2-3 minutes for optimization step (after pre-processing)
  - Pre-processing time dependent on resolution of data
- Process Consistency
  - By using a purposely built tool, with automation capability, consistency across different applications and different users can be ensured
  - Opportunity to put in data quality check points and not allow users to proceed without meeting pre-defined metrics
  - Allows for a wider audience of users

[Electric Machine Calibration Using Model-Based Calibration](#)

Daniel Berry, General Motors

# More Info

## [MathWorks technical article](#)



The screenshot shows the MathWorks website's 'Technical Articles and Newsletters' section. At the top, the MathWorks logo is followed by navigation links: Products, Solutions, Academia, Support, Community, and Events. Below this is a dark blue header bar with the text 'Technical Articles and Newsletters' on the left and a search bar labeled 'Search Technical Articles' on the right. Under the header bar, there is a row of links: Overview, Search Technical Articles, Newsletters (with a dropdown arrow), Cleve's Corner Collection, and Sign Up. The main content area features a large orange title 'Calibrating Optimal PMSM Torque Control with Field-Weakening Using Model-Based Calibration'. Below the title, it says 'By Dakai Hu, MathWorks'. The text describes PMSM calibration as an indispensable step in electric traction drive control design, traditionally involving hardware testing and data processing. It then introduces model-based calibration as a standardized, automated workflow that uses statistical modeling and numeric optimization to calibrate complex nonlinear systems, noting its adoption in internal combustion engine control and its application to e-motor control.

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## Calibrating Optimal PMSM Torque Control with Field-Weakening Using Model-Based Calibration

By Dakai Hu, MathWorks

Permanent magnet synchronous motor (PMSM) calibration is an indispensable step in the design of high-performance electric traction drive controls. Traditionally, the calibration process involves extensive hardware dynamometer (dyno) testing and data processing, and its accuracy depends largely on the expertise of the calibration engineer.

Model-based calibration standardizes the PMSM calibration process, reduces unnecessary testing, and generates consistent results. It is an industry-proven, automated workflow that uses statistical modeling and numeric optimization to optimally calibrate complex nonlinear systems. It can be used in a wide range of applications and is well known for being adopted in internal combustion engine control calibration. When applied to e-motor control calibration, the model-based calibration workflow can help motor control engineers achieve optimal torque and field-weakening control for PMSMs.

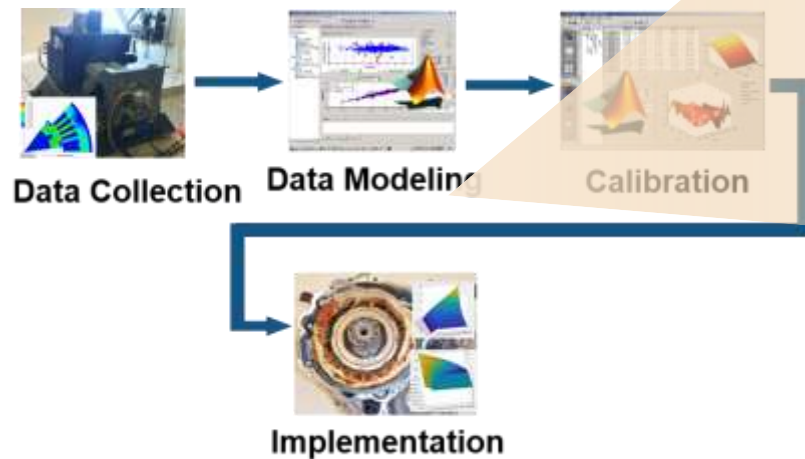
### PMSM Characterization and Calibration: Challenges and Requirements

PMSMs stand out from other types of e-motors because of their high efficiency and torque density. This is because the permanent magnets inside the machine can generate substantial air gap magnetic flux without external excitation. This special trait makes a PMSM an excellent candidate for both non-traction and traction motor drive applications.



# コンサルティング サービス

- サービス内容
  - MBCワークフローに関するアドバイス
  - ツールの基本操作をレクチャ
  - データの前処理支援
  - GUIでMBCワークフローを構築



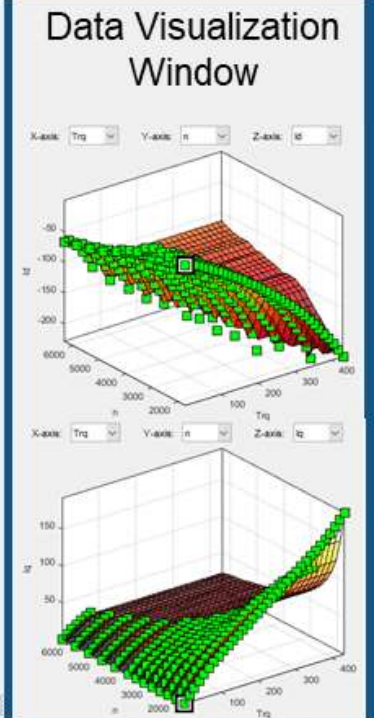
## Calibration Workflow

The **Motor Calibration** GUI (V1.0) is divided into several sections:

- Motor Parameters:** Includes input fields for  $V_{max}$ ,  $I_{max}$ , Torque Minimum, Torque Maximum, Speed Maximum, and Speed Minimum, all currently set to 0.
- Data Process:** Features buttons for "Import Data" and "Test Data", and dropdown menus for X Axis, Y Axis, and Z Axis, all set to "Option 1". A "Plot" button is also present.
- Fit Models:** Includes input fields for Torque Tolerance and Speed Tolerance (both 0), and a "Fit Models" button. The RMSE is displayed as 0.
- Generate Calibration:** Contains a "Generate Calibration" button and buttons for "Id Table" and "Iq Table".

Red brackets above the GUI indicate that the left side (Motor Parameters, Data Process, Fit Models, Generate Calibration) corresponds to the **Calibration Workflow**, and the right side (Data Visualization Window) corresponds to **Visualization**.

## Visualization

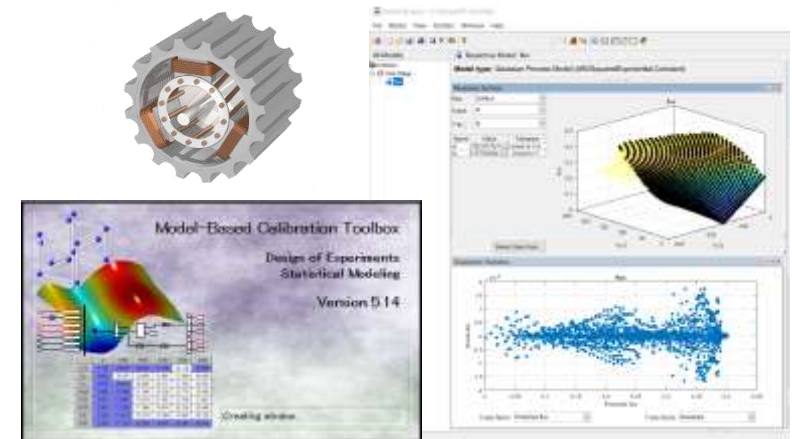


## まとめ

- **本セッションの説明内容の振り返り**
  - ✓ Model-Based Calibration Toolboxを活用したIPMSMの弱め磁束制御テーブルのキャリブレーション方法を紹介
- **MATLAB製品の強み**
  - ✓ 一気通貫で設計意図を伝搬する製品群 & 効率的に作業が行える環境を提供
  - ✓ 豊富な例題を備えたドキュメントやテクニカルサポート・トレーニング・コンサルを提供



モーターをキャリブレーションする際は、  
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