



ROBUST DEVELOPMENT OF ELECTRIC POWERTRAIN NVH FOR COMPACT ELECTRIC SUV

TAE-WON HA, HYUNDAI MOTOR COMPANY



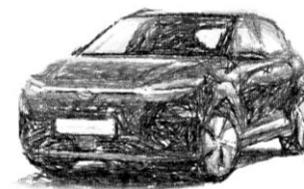
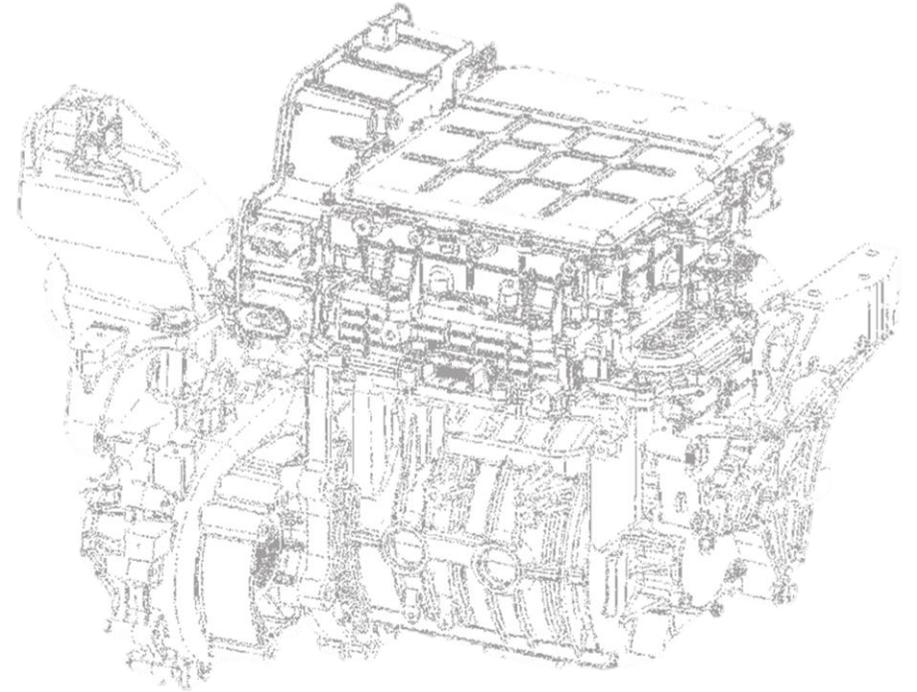
Introduction

Background and Motivation

e-Motor Whining noise

e-PT Droning Noise

Conclusion

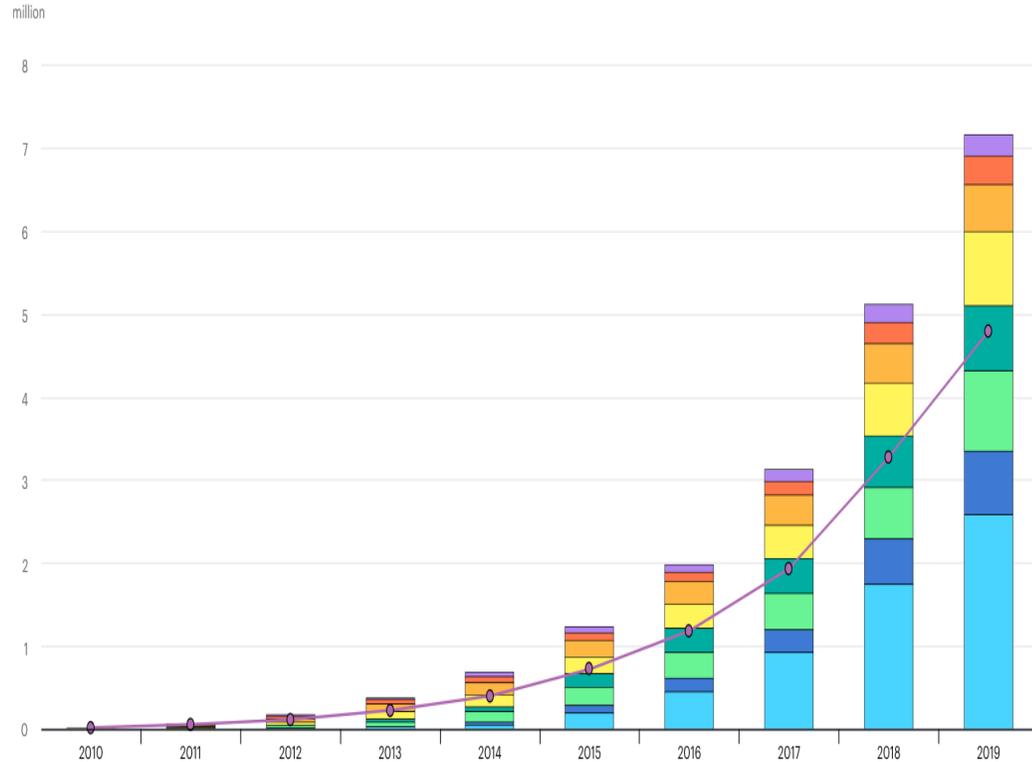


Introduction

NEW THINKING.
NEW POSSIBILITIES.

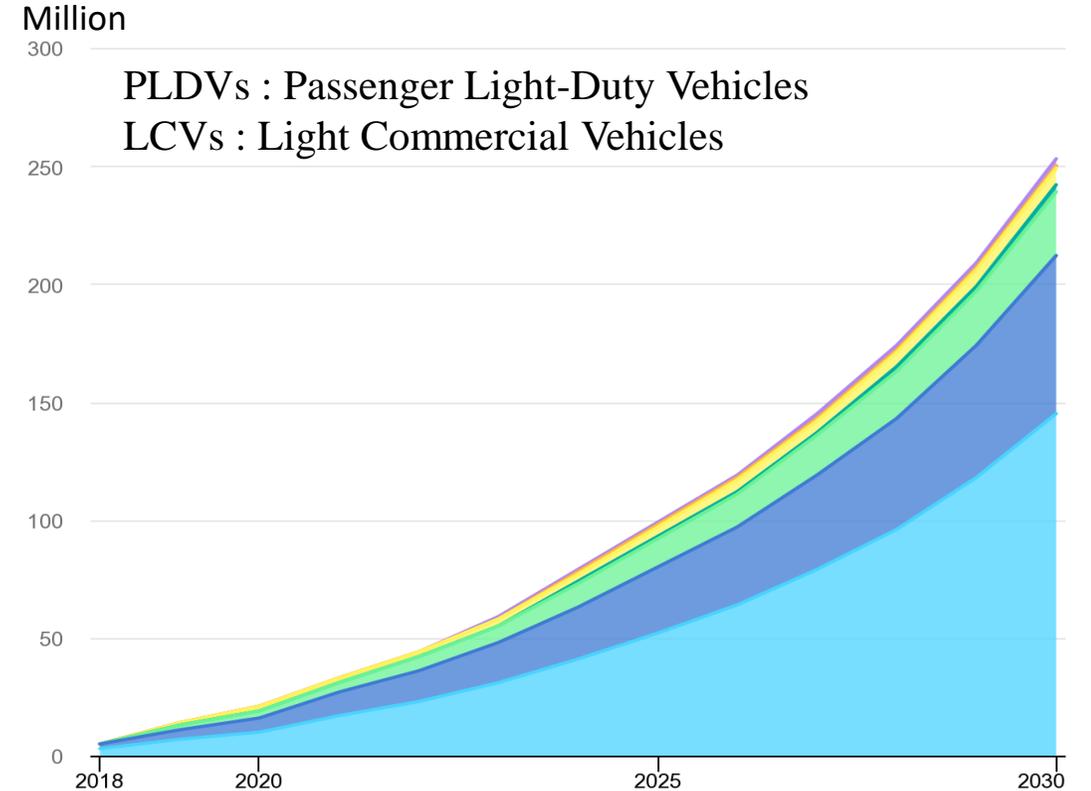
◆ EV market growth status and forecast

China BEV China PHEV Europe BEV Europe PHEV United States BEV United States PHEV Other BEV Other PHEV World BEV



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PLDVs - BEV PLDVs - PHEV LCVs - BEV LCVs - PHEV Buses - BEV Buses - PHEV Trucks - BEV Trucks - PHEV



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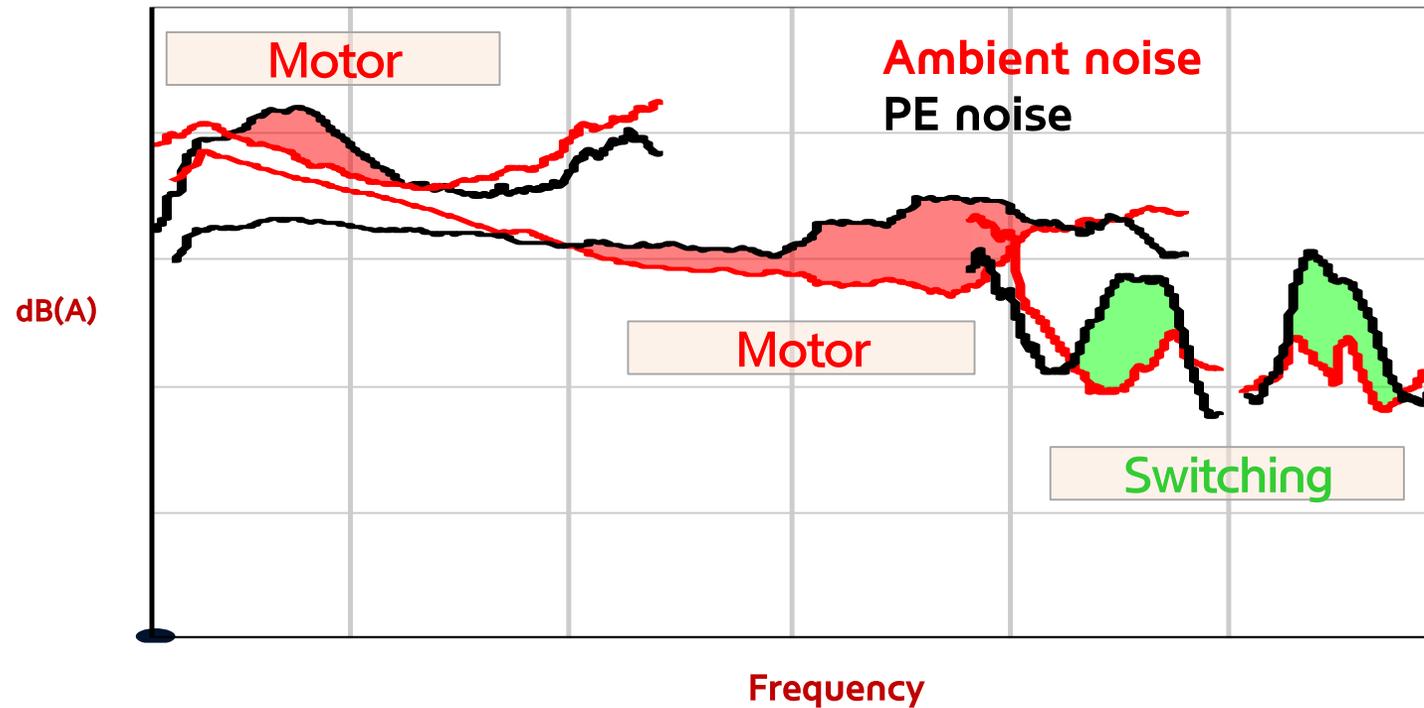
Introduction

NEW THINKING.
NEW POSSIBILITIES.

◆ Electric vehicle noise characteristics

Example of EV Sound Quality

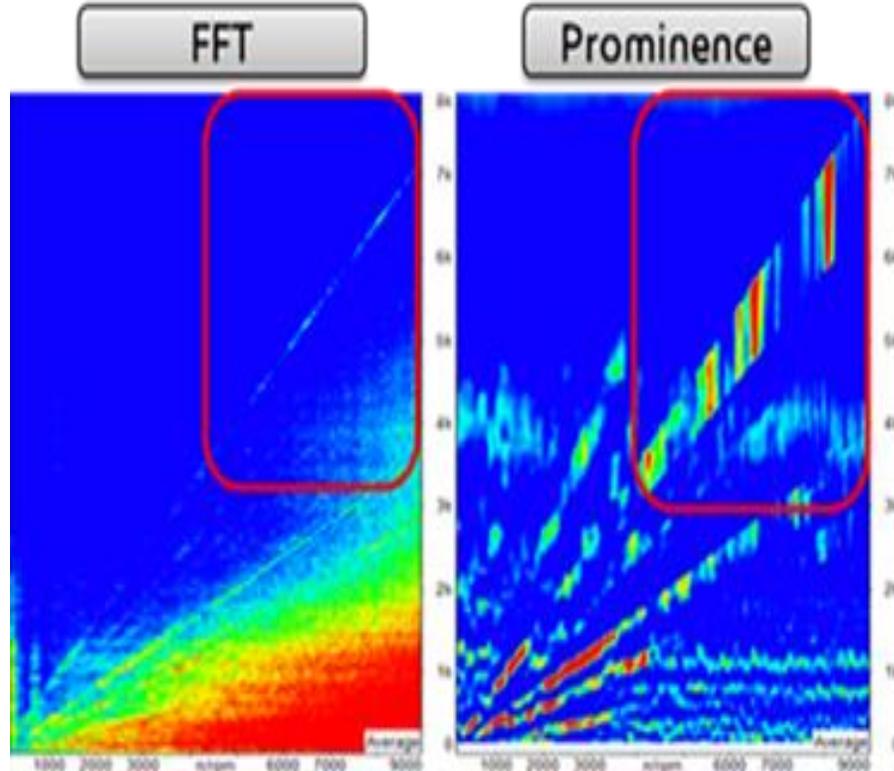
Shaded area (PE noise > Ambient noise)
: PE noise problem areas



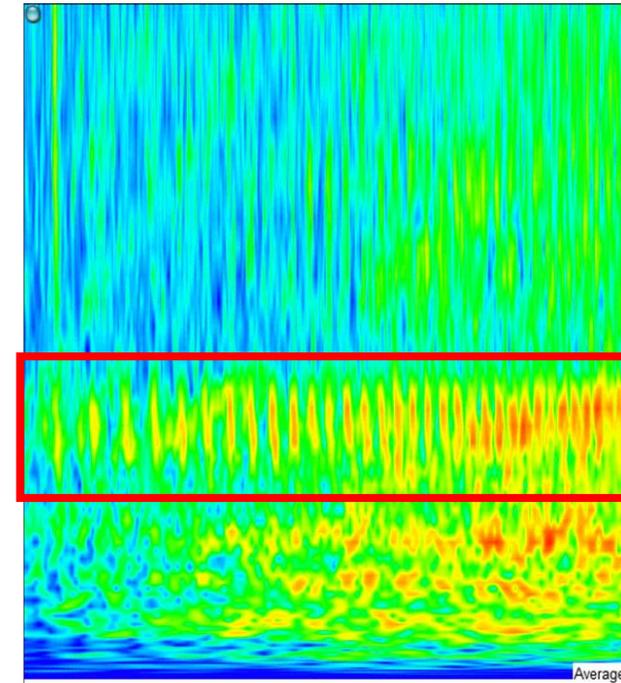
Background and Motivation

NEW THINKING.
NEW POSSIBILITIES.

Motor Noise



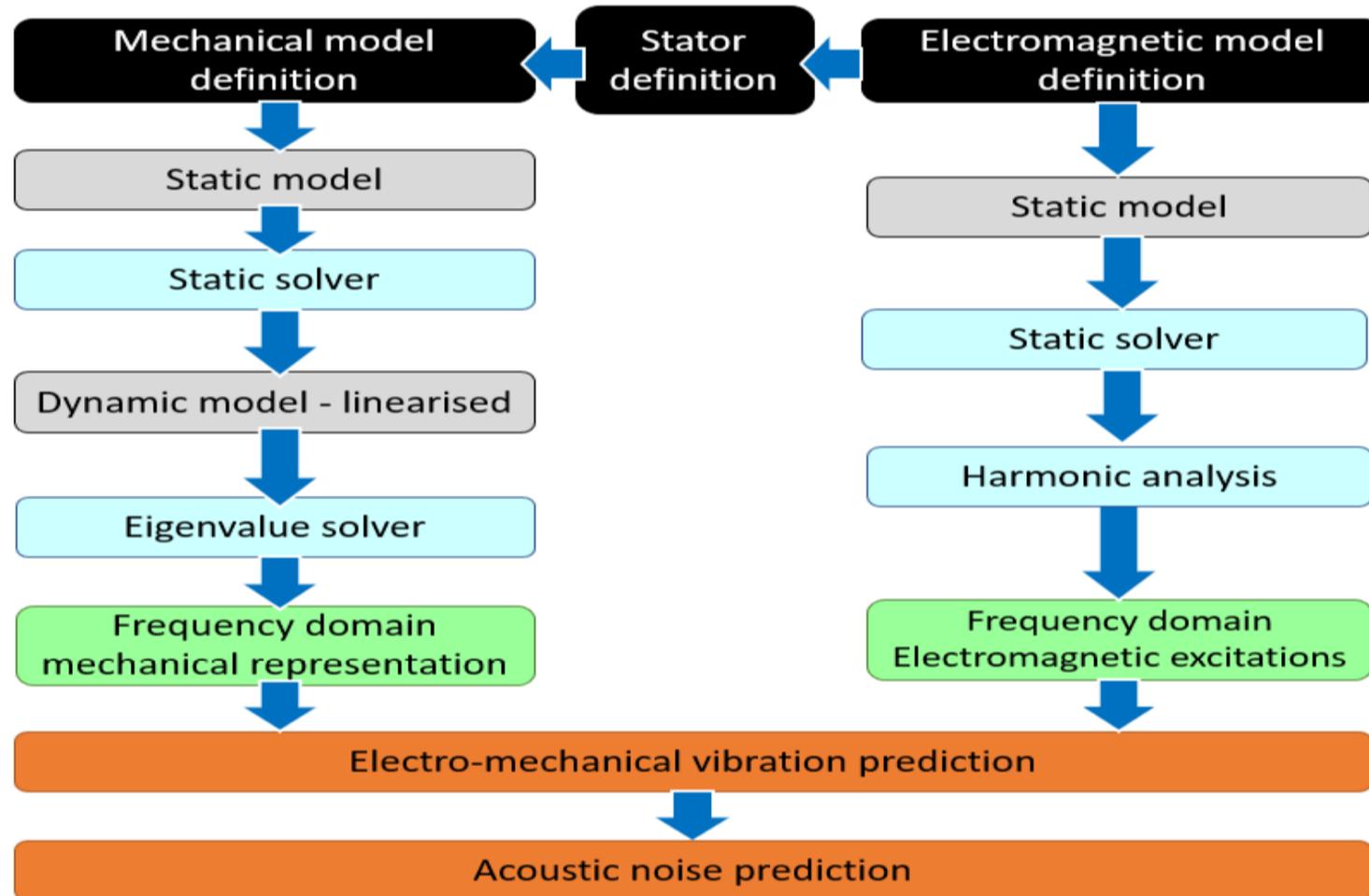
Droning Noise



E-Motor Whining noise

NEW THINKING.
NEW POSSIBILITIES.

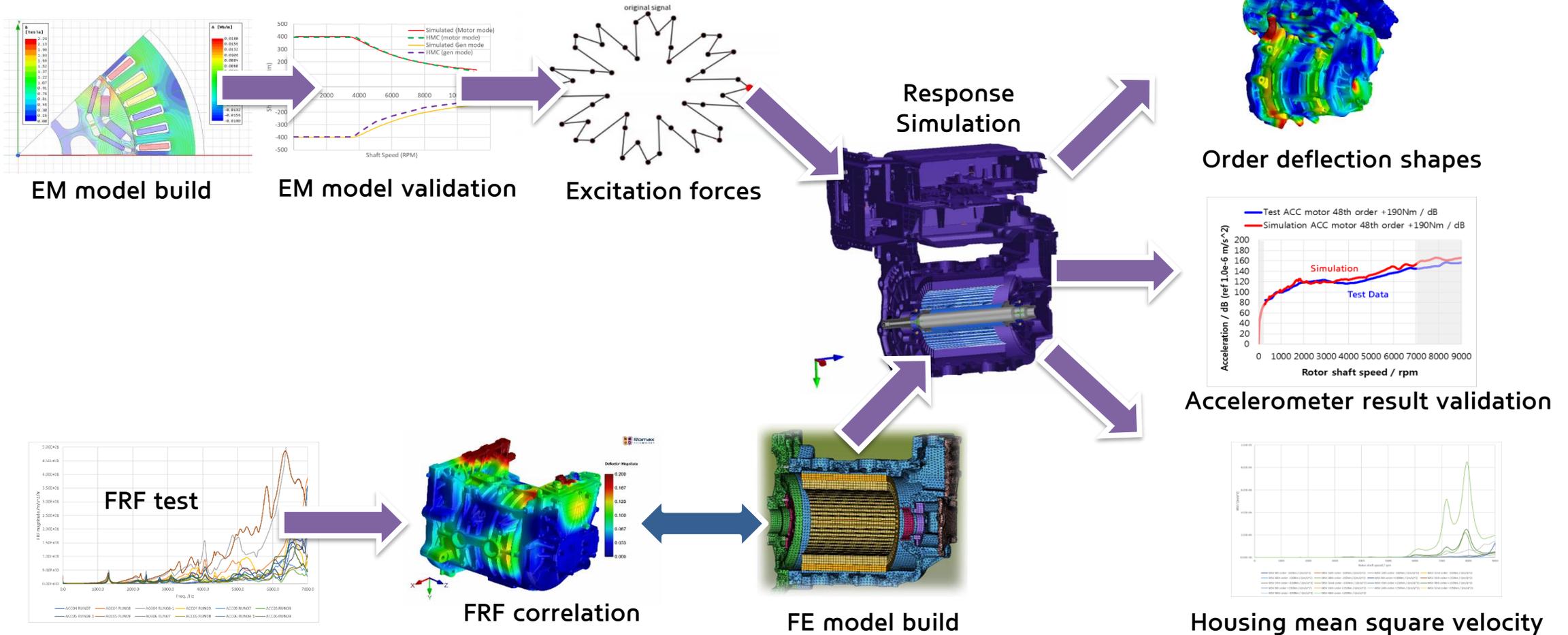
◆ Work Flow for E-Motor noise prediction



E-Motor Whining noise

NEW THINKING.
NEW POSSIBILITIES.

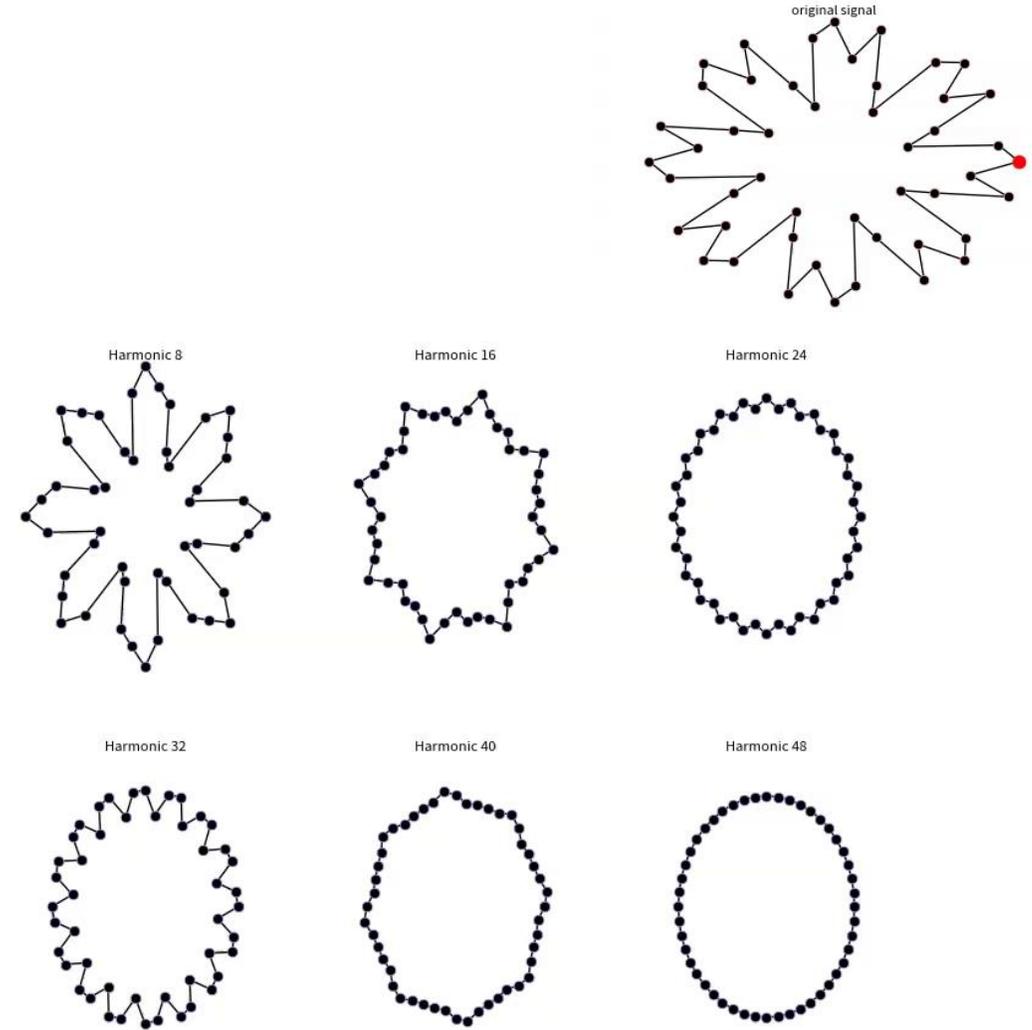
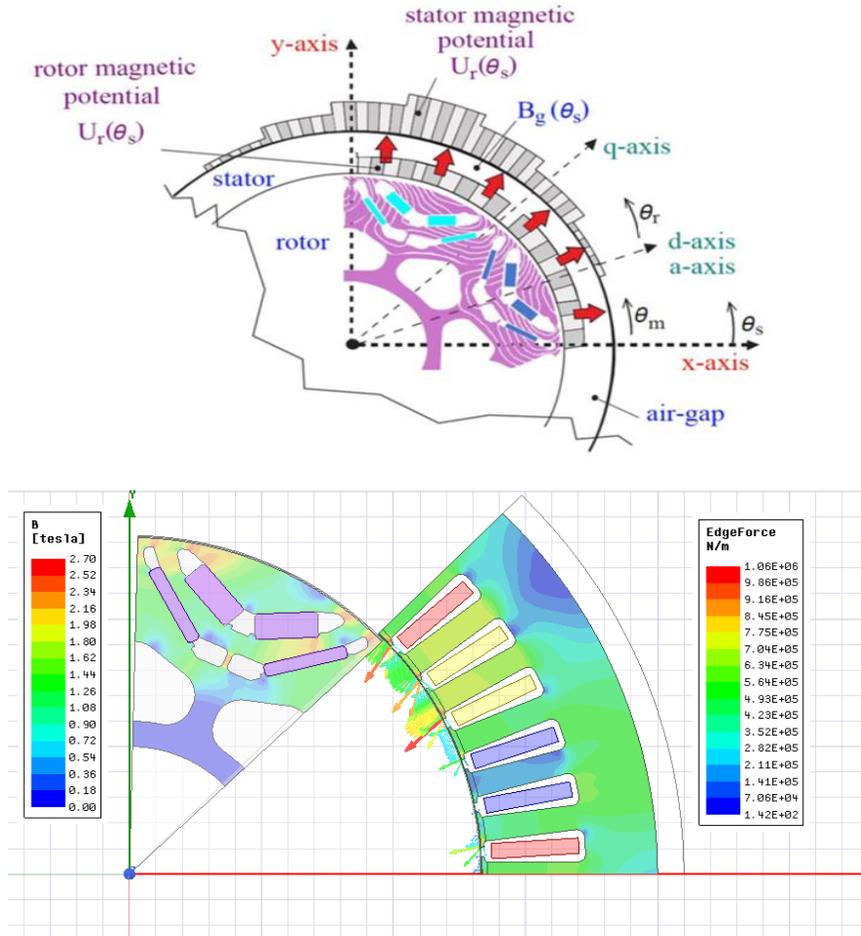
◆ Work Flow for E-Motor noise prediction



■ E-Motor Whining noise

NEW THINKING.
NEW POSSIBILITIES.

◆ Electromagnetic Excitation of E-Motor

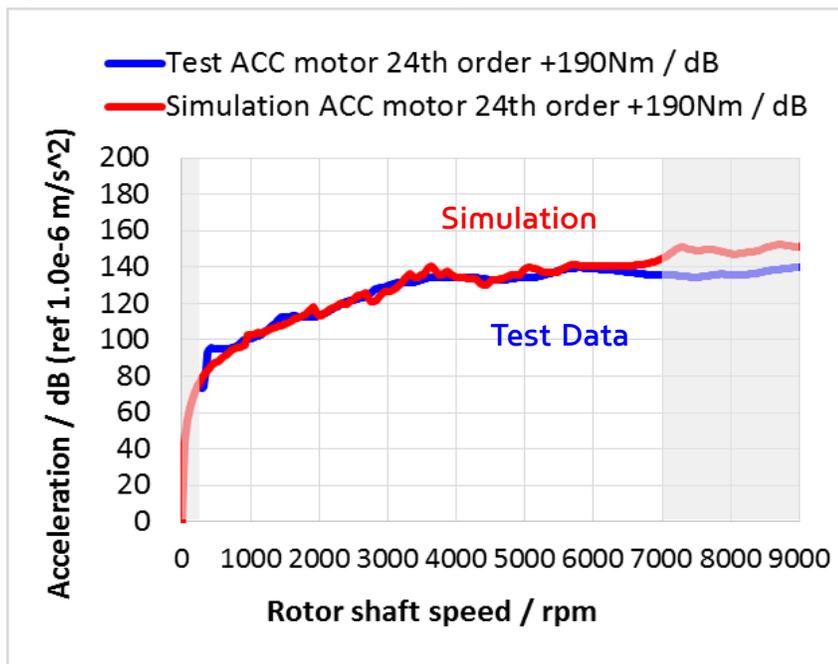


E-Motor Whining noise

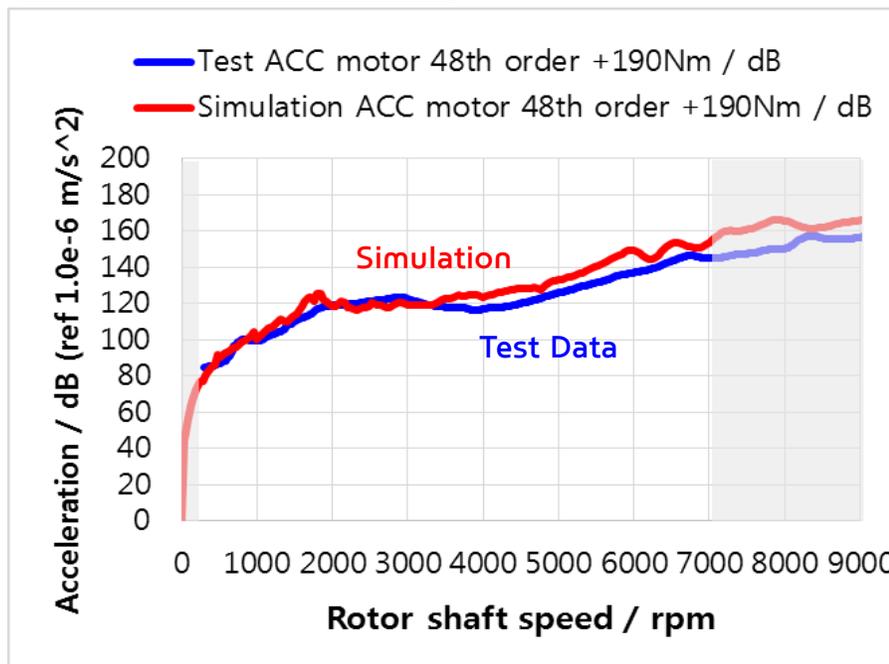
NEW THINKING.
NEW POSSIBILITIES.

◆ Simulation Model Validation

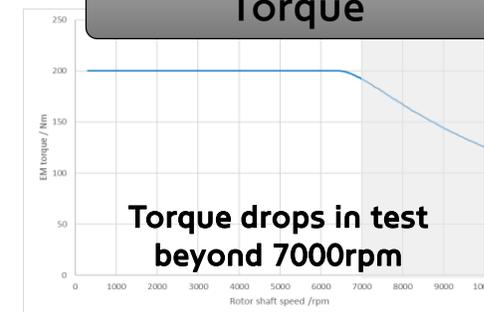
24th EM order



48th EM order



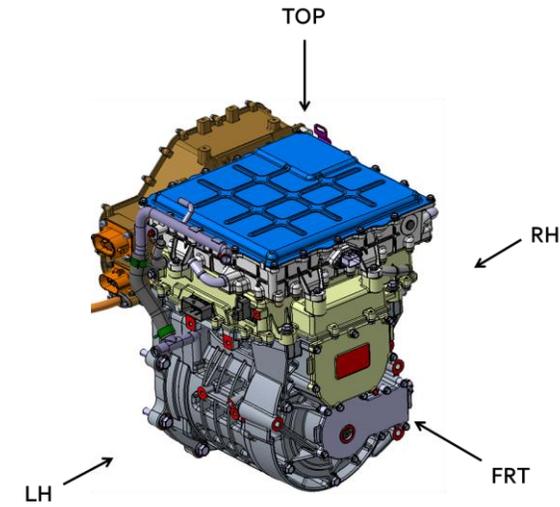
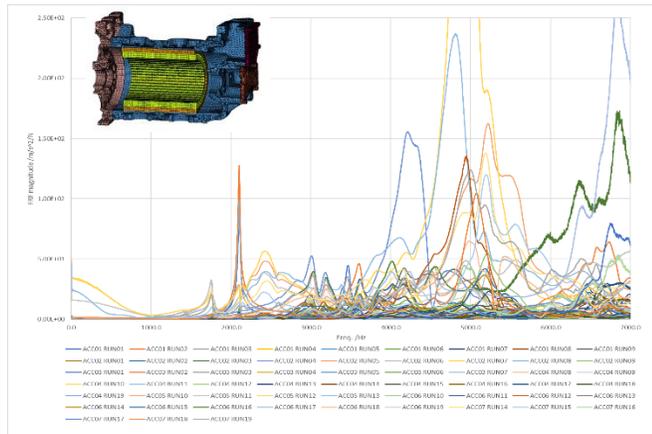
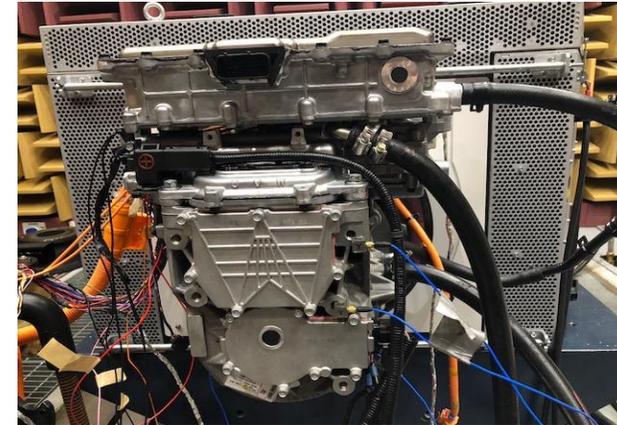
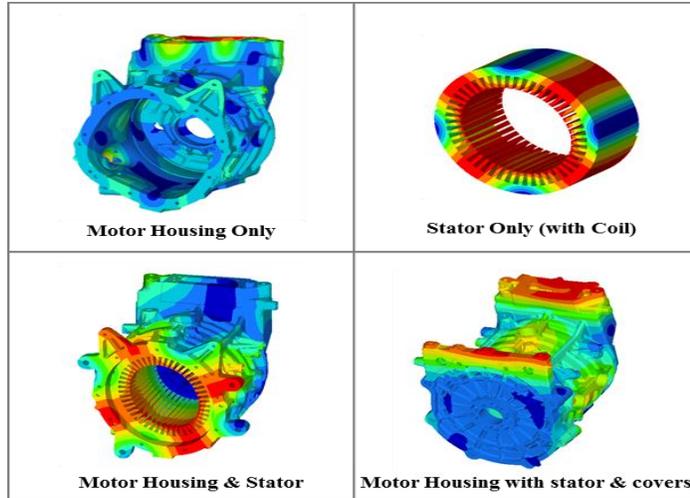
Torque



E-Motor Whining noise

NEW THINKING.
NEW POSSIBILITIES.

◆ Test for model validation



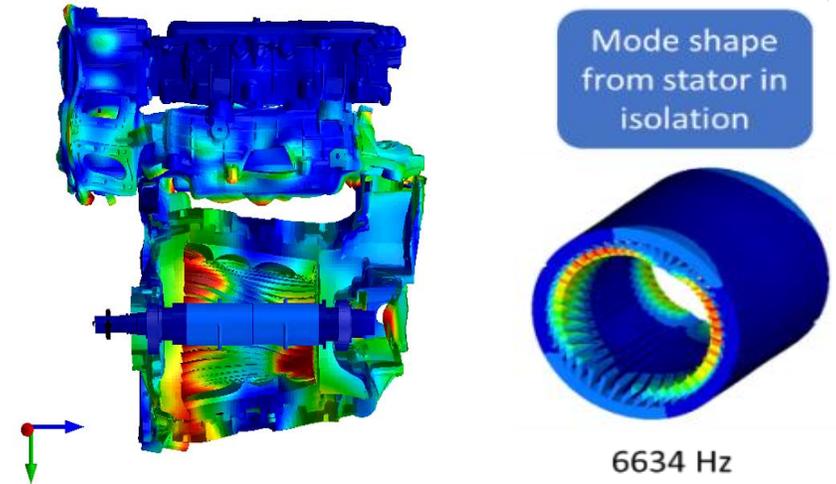
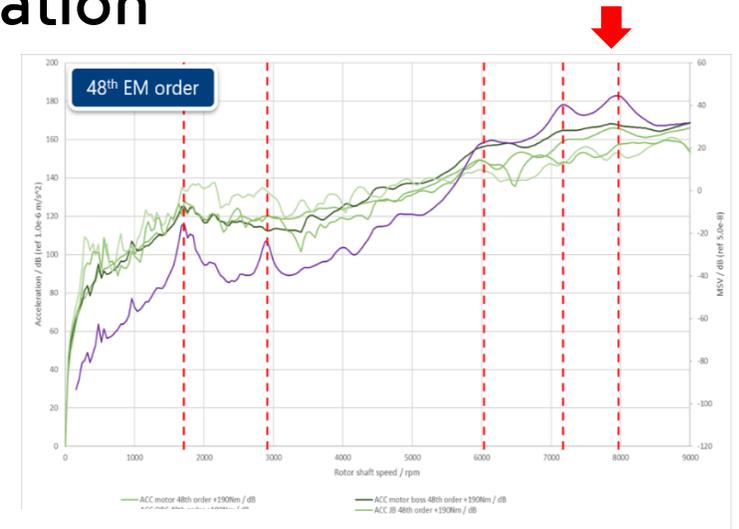
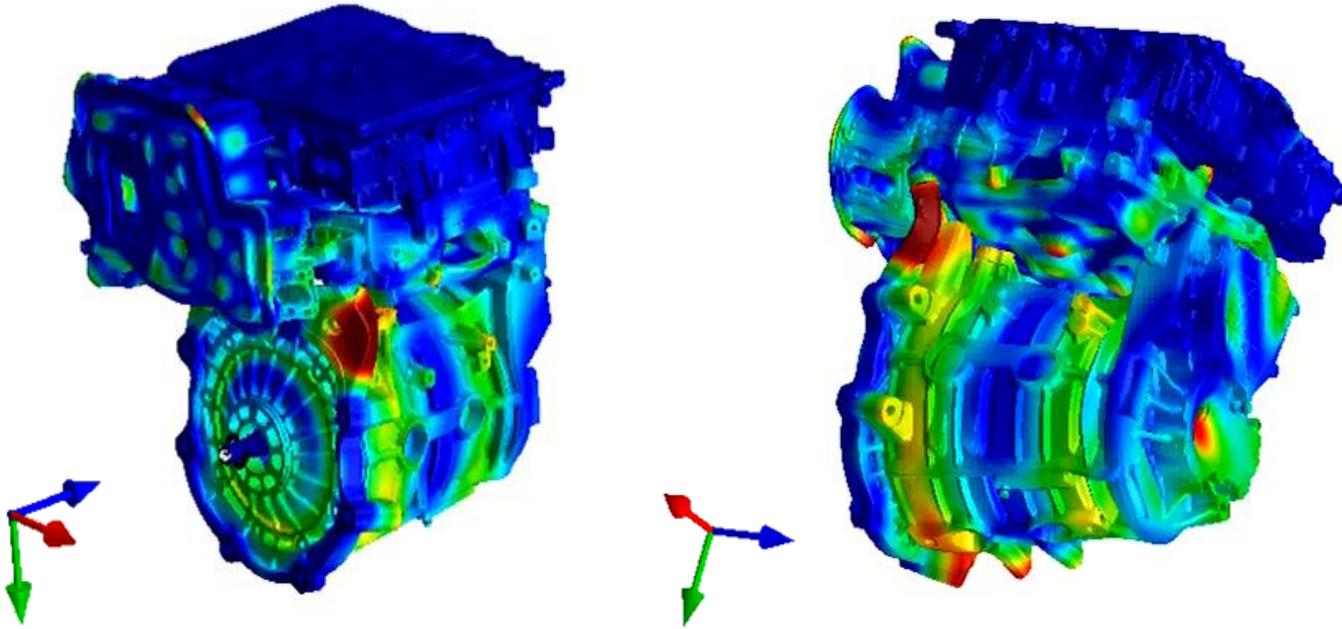
E-Motor Whining noise

NEW THINKING.
NEW POSSIBILITIES.

◆ Vibration response based on electromagnetic excitation

Operating Deflection Shape (ODS) results

- 48th order, 7960 rpm (6368 Hz)

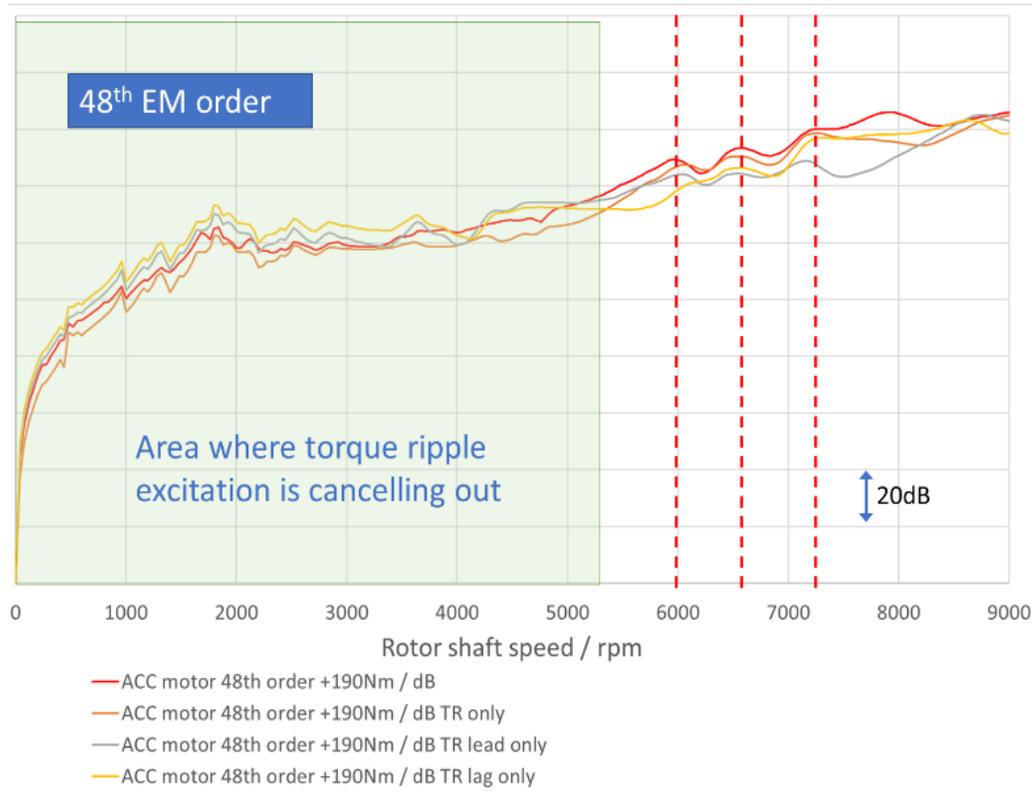


E-Motor Whining noise

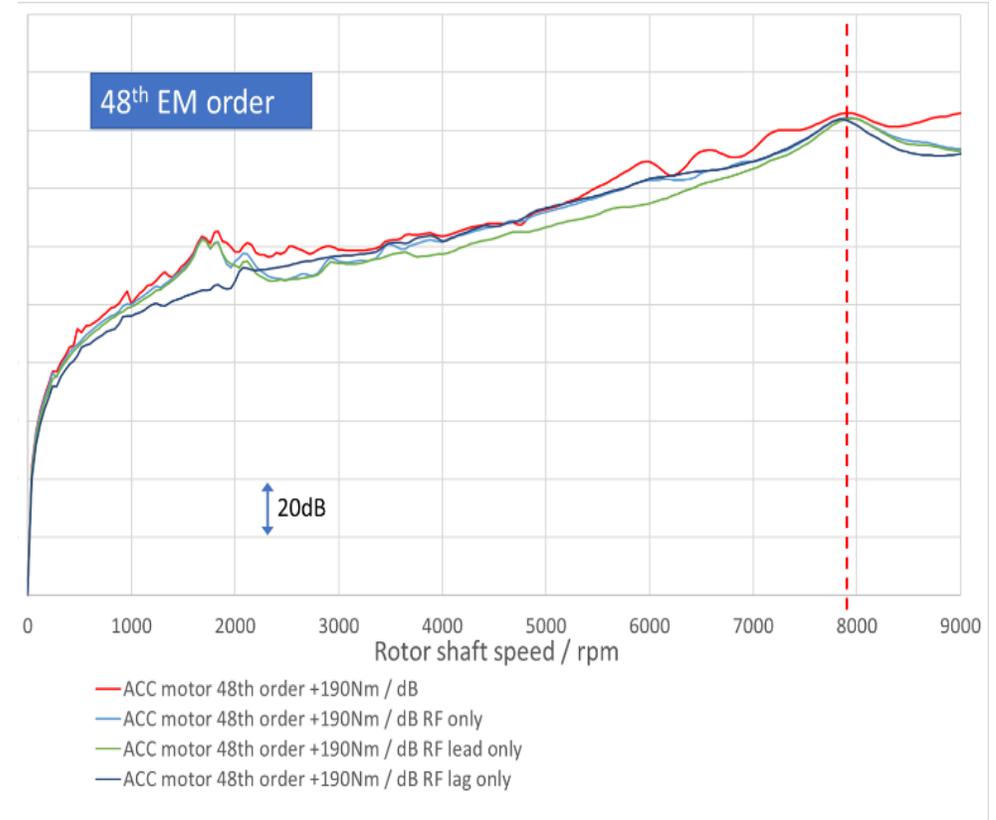
NEW THINKING.
NEW POSSIBILITIES.

◆ Response contribution for each electromagnetic excitation force

Torque Ripple Contribution

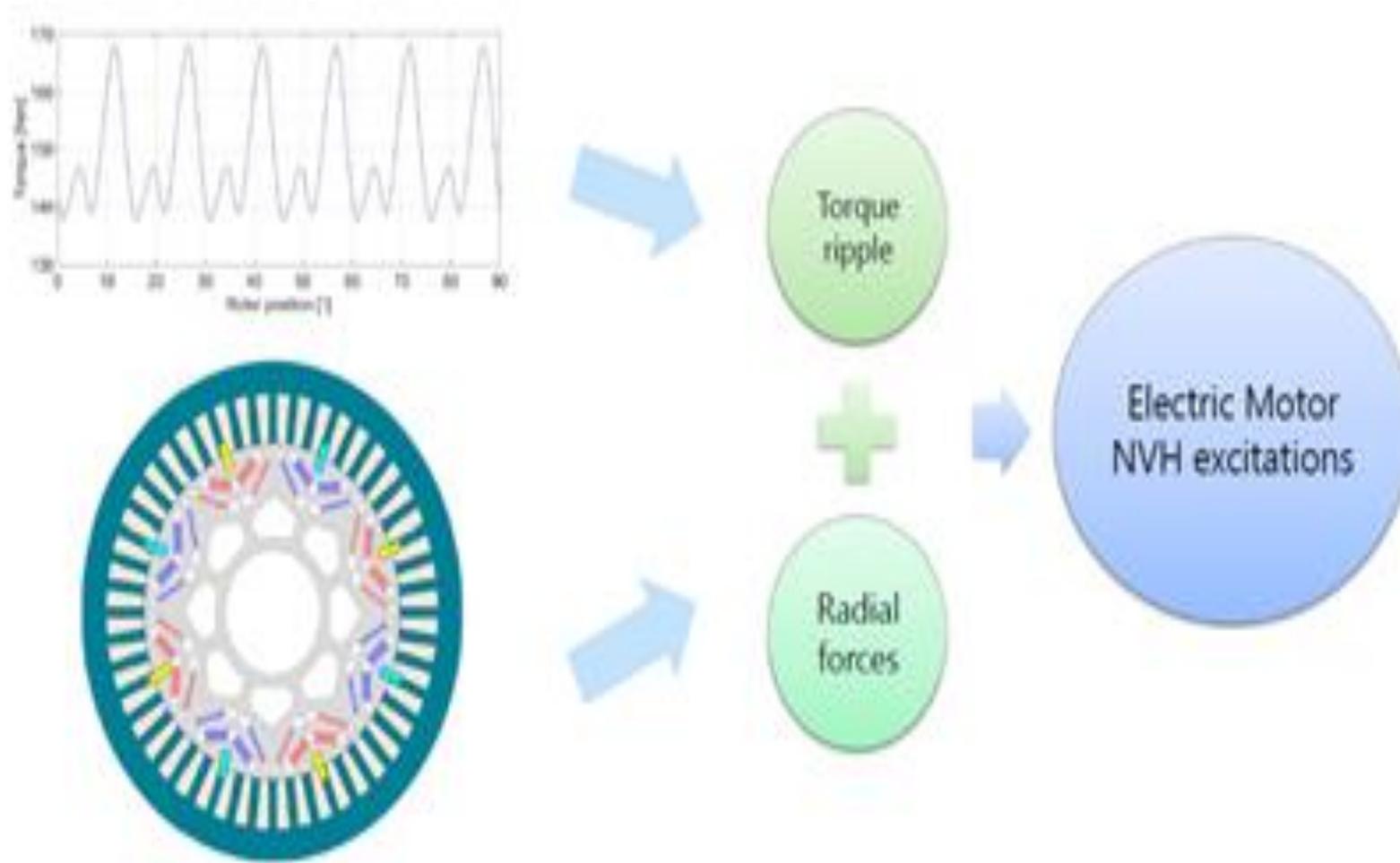


Radial Force Contribution

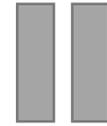


■ E-Motor Whining noise

NEW THINKING.
NEW POSSIBILITIES.



Design
Improvement Plan



Structural design
modification



Motor geometry
modification

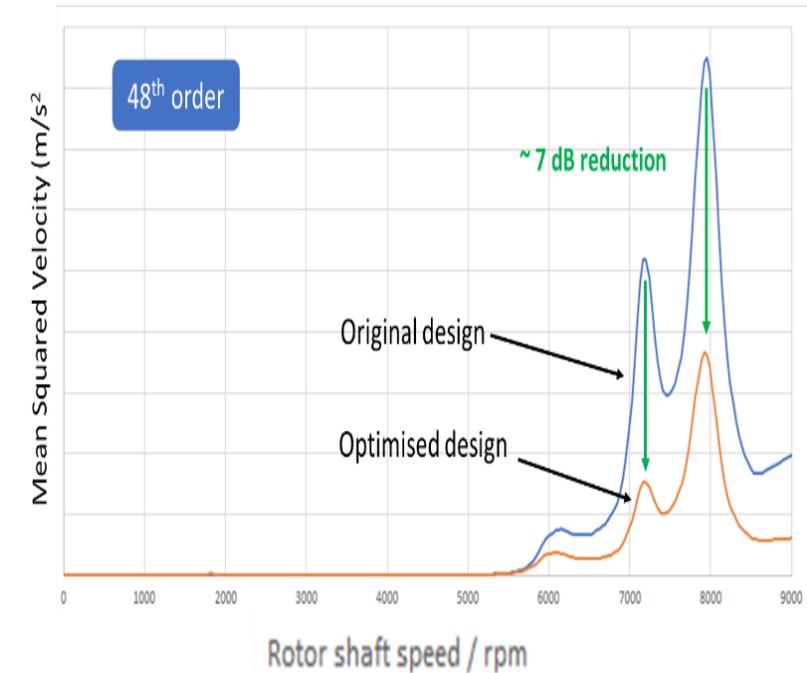
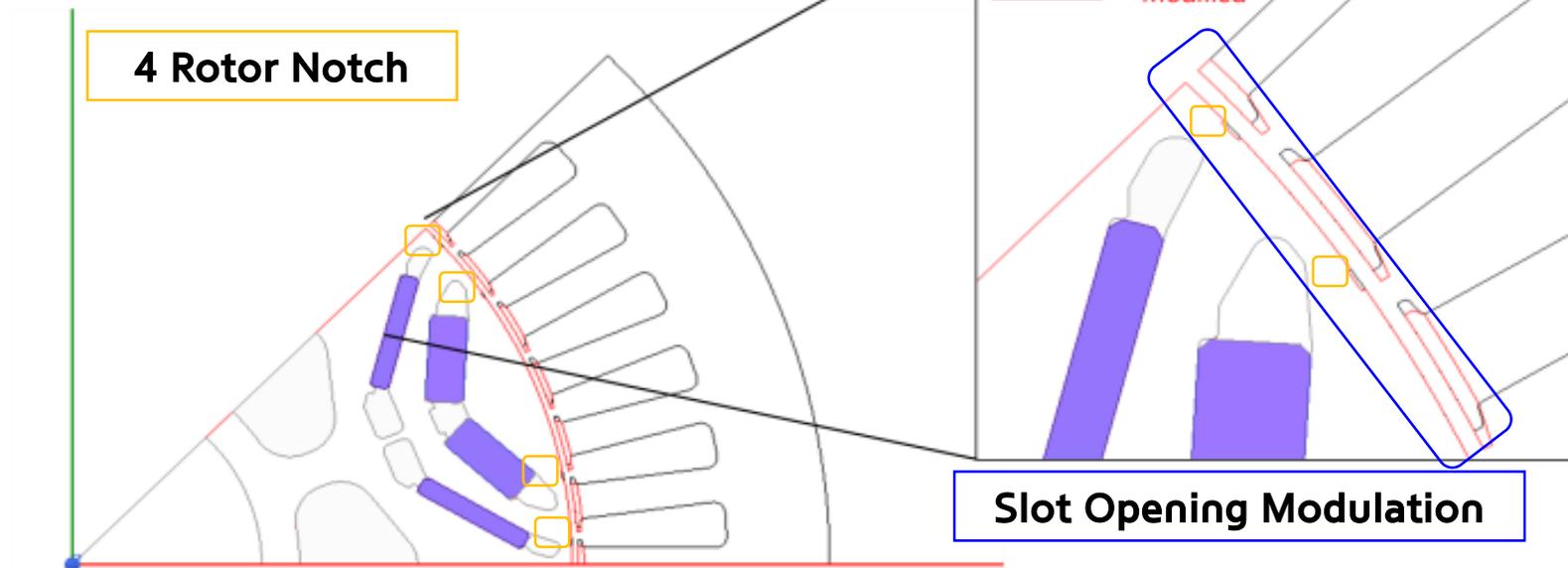
■ E-Motor Whining noise

NEW THINKING.
NEW POSSIBILITIES.

◆ E-Machine Design Optimization

- Motor design was optimized avoiding fundamental changes in machine performances/type of machine.
 - Slot opening modulation (SOM)
 - Four rotor notches (FRN)

Geometry modifications



■ E-Motor Whining noise

NEW THINKING.
NEW POSSIBILITIES.

◆ 1st topic summary and conclusions

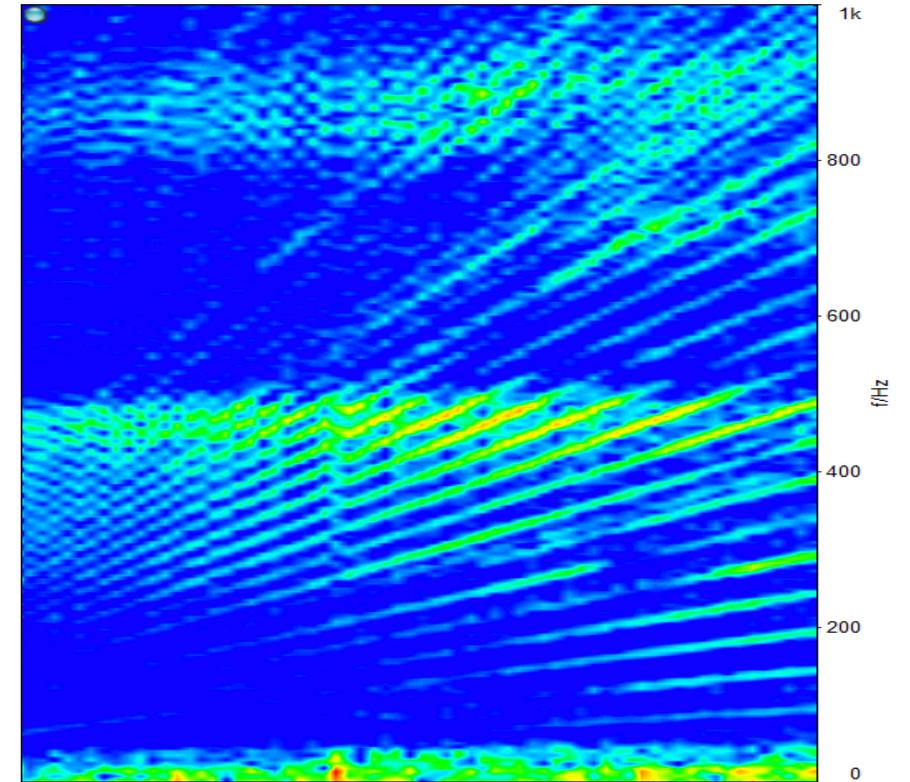
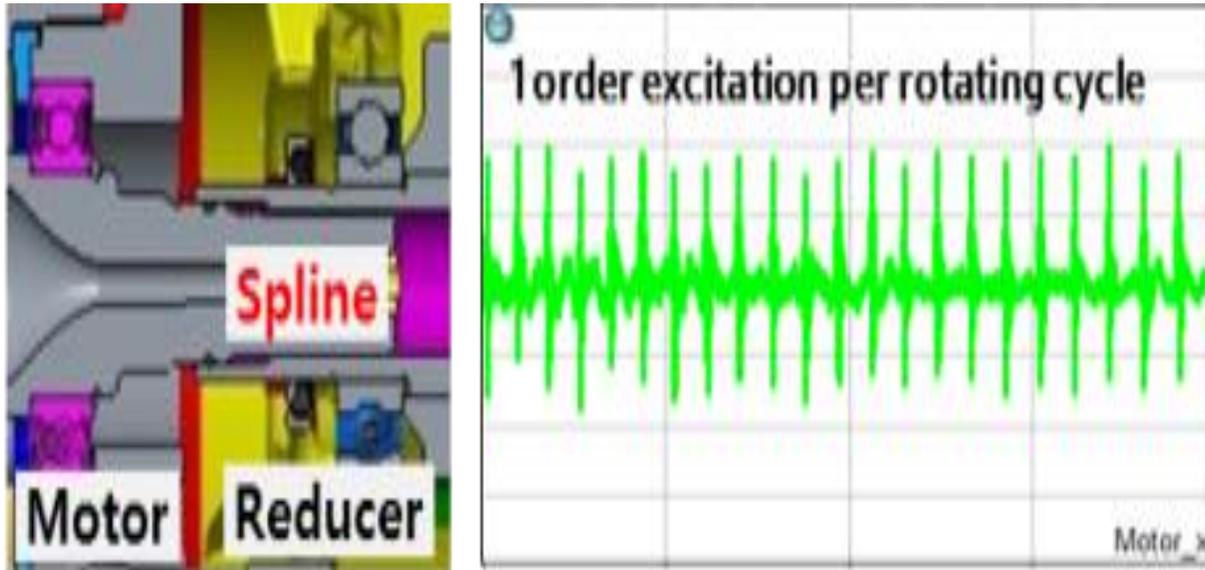
- **Good correlation** has been achieved between the **simulation model and test results**
- **48th order electromagnetic excitation dominates** the vibration response of the system
- **Unique insight** has been gained regarding the **transfer of the source of the vibration and response of the system** across the frequency range of interest for understanding the NVH behavior.
- With this approach, **system can be created before a structure is built and tested** then used for design modification and optimization in the **early development phase, reducing development time and risk.**
- **Importance of simulating the relevant parameters in detail** to identify potential for **system level improvement through component level optimization.**



■ e-PT Droning Noise

NEW THINKING.
NEW POSSIBILITIES.

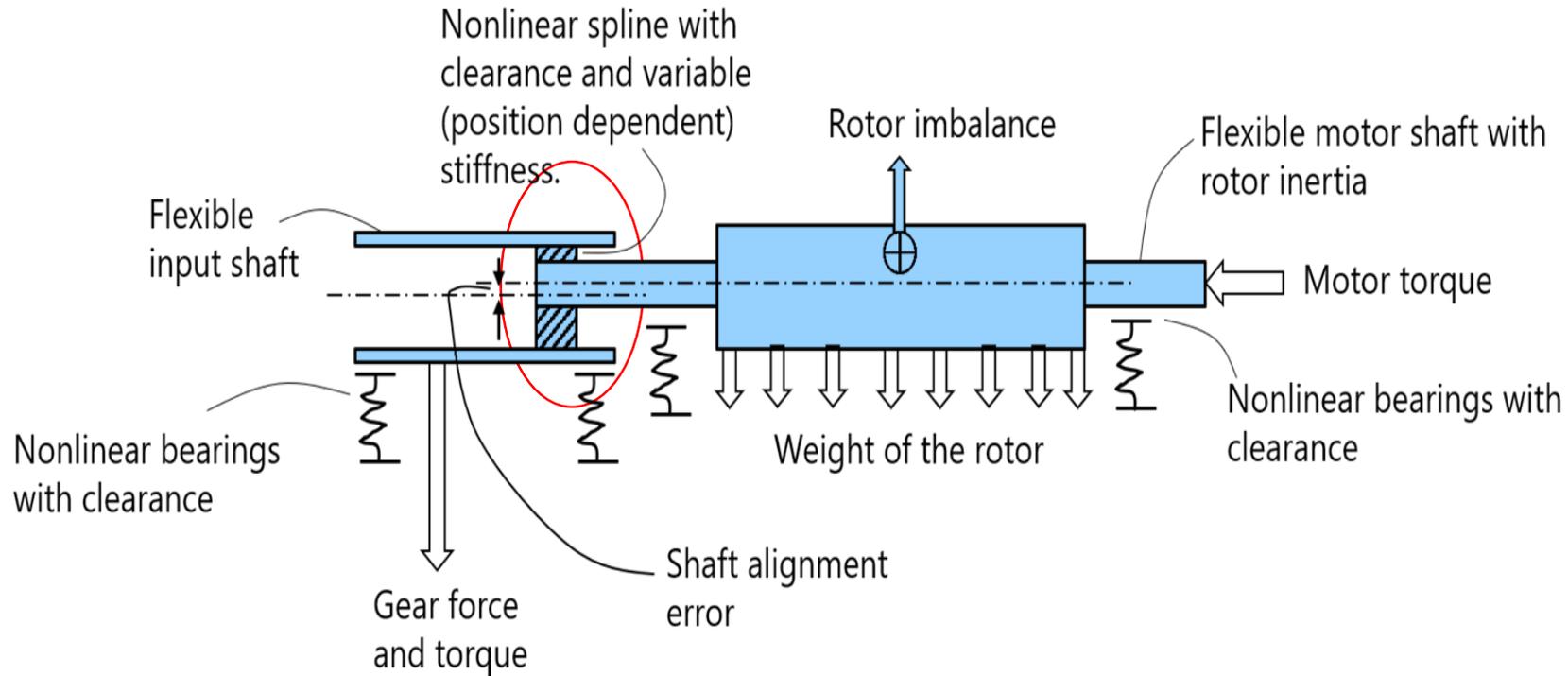
◆ Problem phenomenon



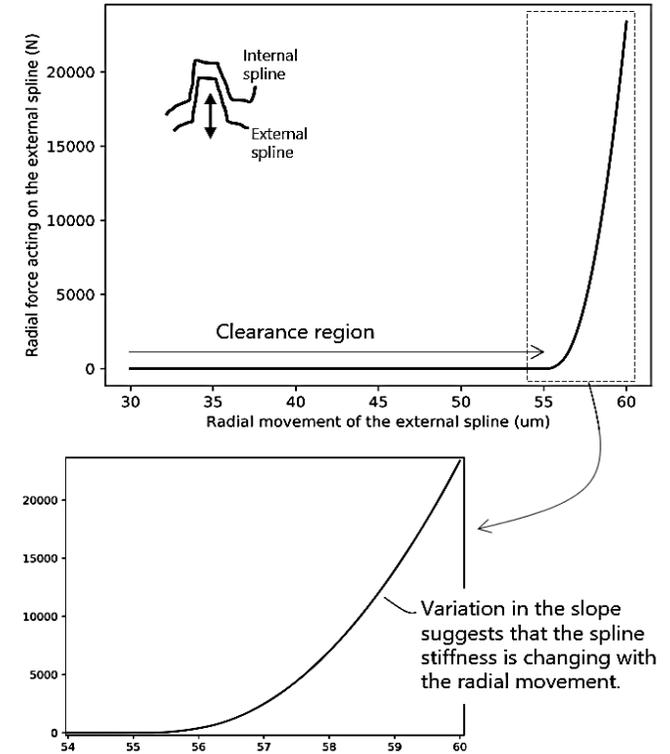
■ e-PT Droning Noise

NEW THINKING.
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◆ Modeling



Spline Stiffness Modeling



■ e-PT Droning Noise

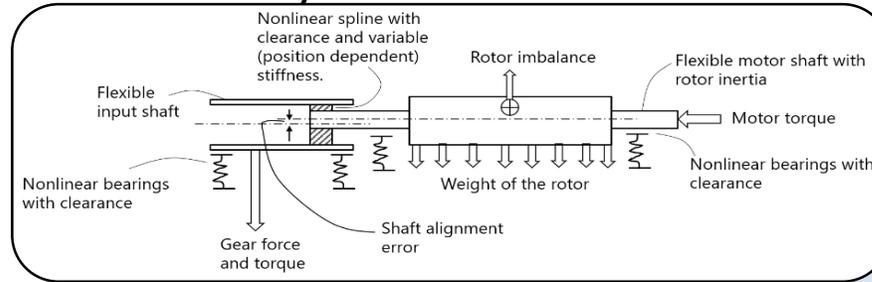
NEW THINKING.
NEW POSSIBILITIES.

◆ Work Flow for reproducing Droning noise

Inputs to the multi-body model

- Motor torque
- Motor speed
- Gear forces and moments
- Spline pitch error
- Spline alignment error

Multi-body model



t, x, \dot{x}

$K(t, x, \dot{x})$
 $C(t, x, \dot{x})$
 $f(t, x, \dot{x})$

Time steps of
ODE integrator

$$\begin{pmatrix} \ddot{x} \\ \dot{x} \end{pmatrix} = \begin{pmatrix} -M^{-1}C(t, x, \dot{x}) & -M^{-1}K(t, x, \dot{x}) \\ I & 0 \end{pmatrix} \begin{pmatrix} \dot{x} \\ x \end{pmatrix} + \begin{pmatrix} M^{-1}f(t, x, \dot{x}) \\ 0 \end{pmatrix}$$

Governing differential equation

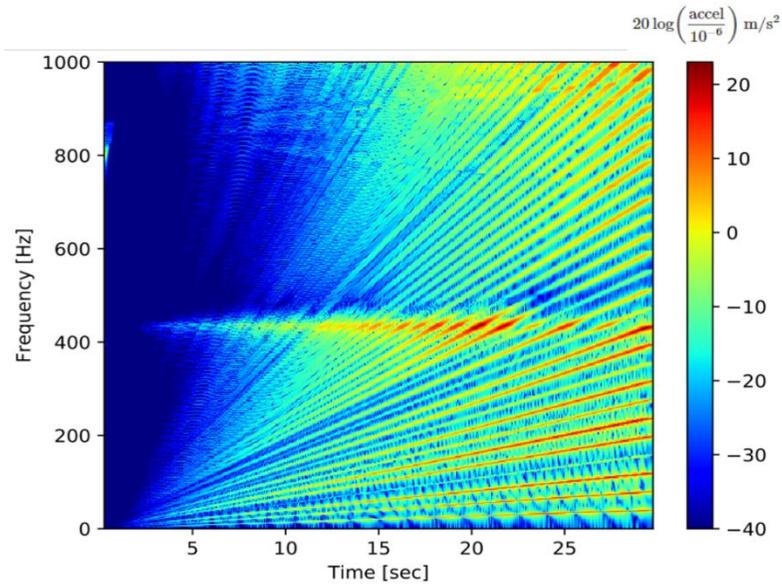
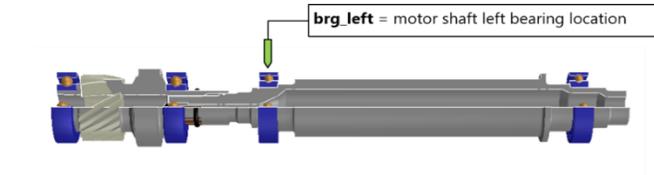
x, \dot{x}

Integrated solution

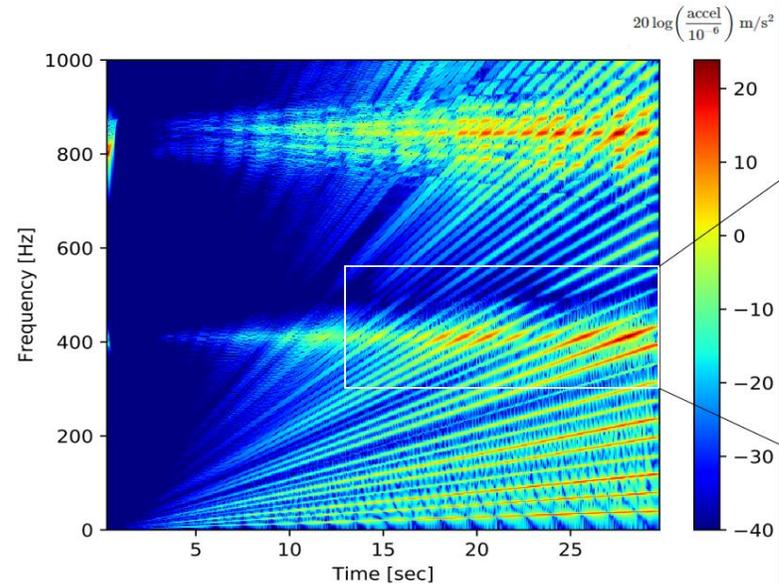
■ e-PT Droning Noise

NEW THINKING.
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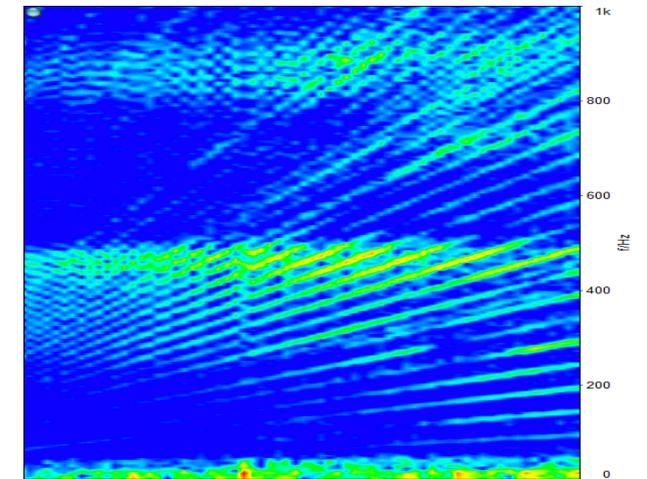
◆ Comparison of test and simulation results



Motor shaft acceleration in X at the left bearing location.



Motor shaft acceleration in Y at the left bearing location.

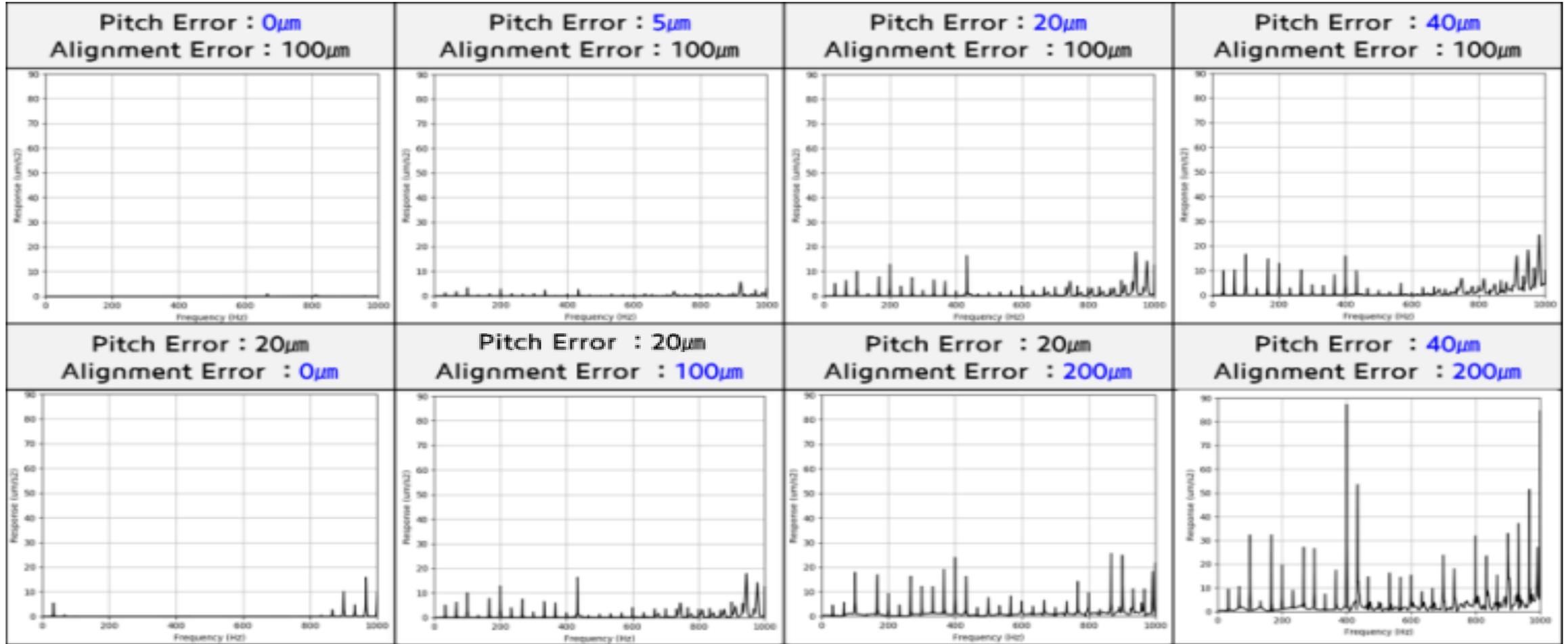


Vibration Response at Motor Housing

■ e-PT Droning Noise

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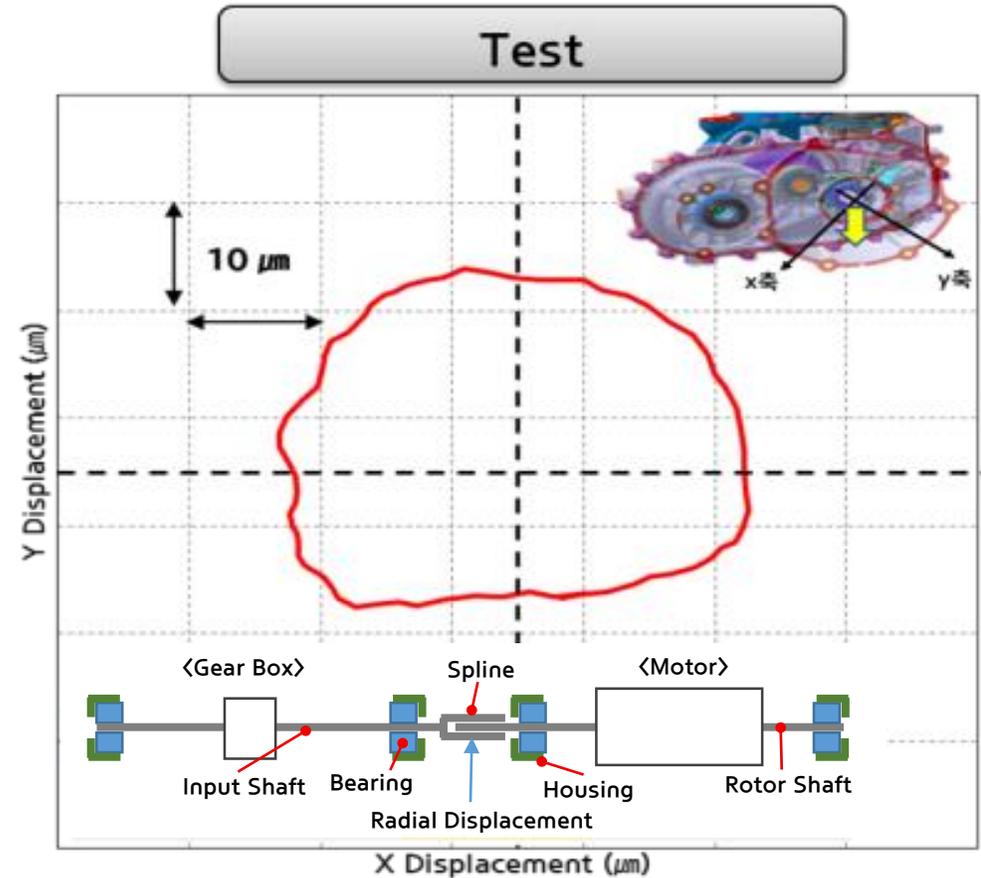
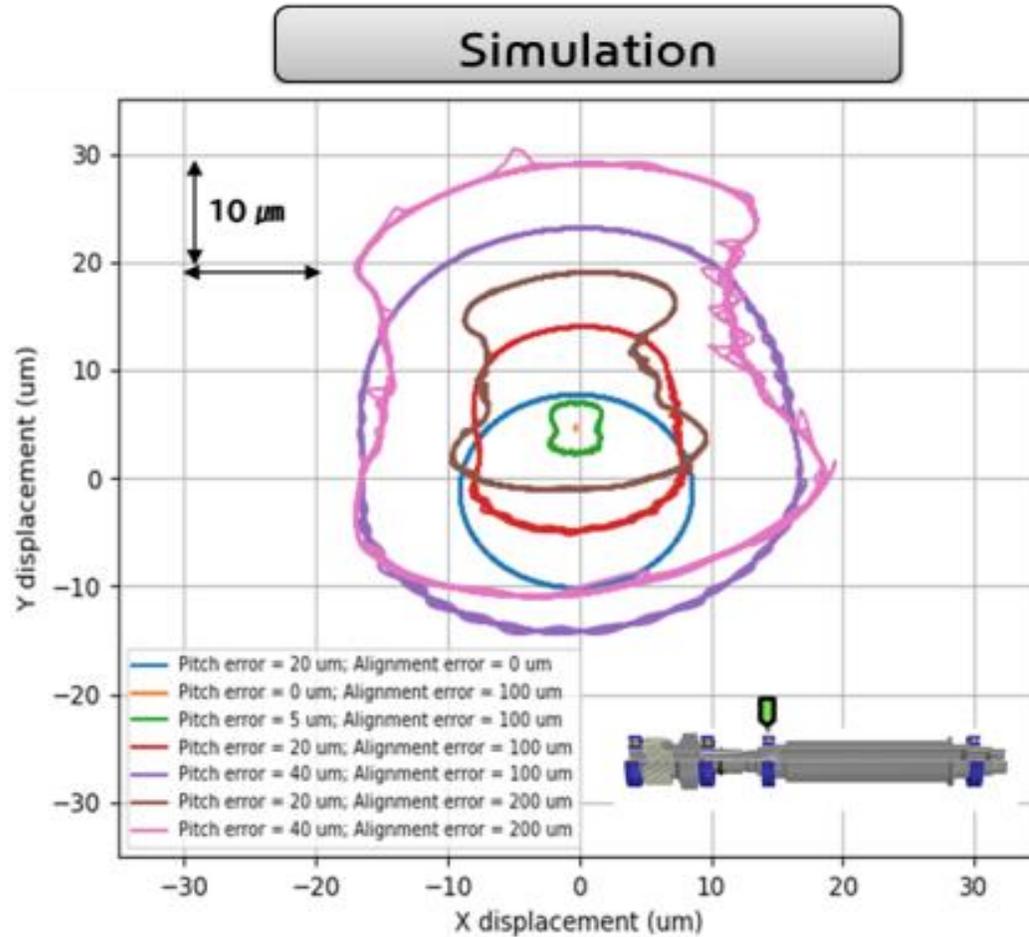
◆ Parameter Study



■ e-PT Droning Noise

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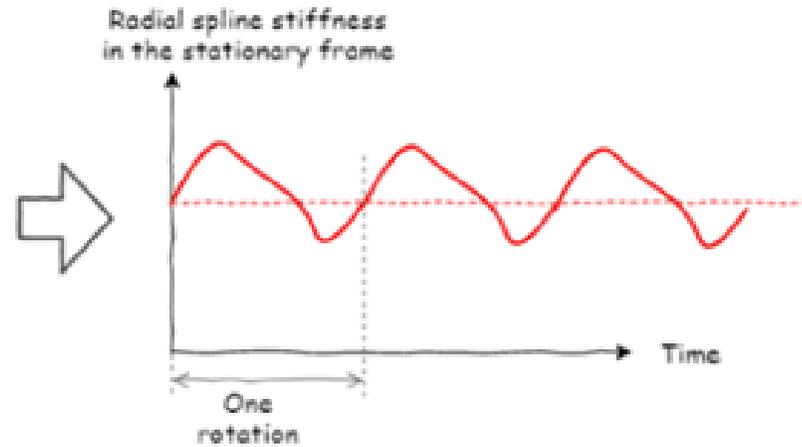
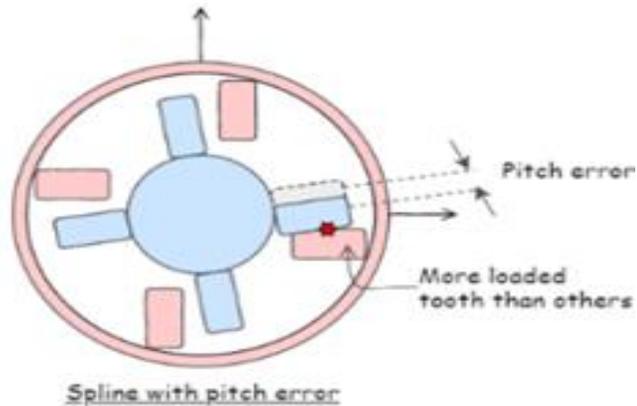
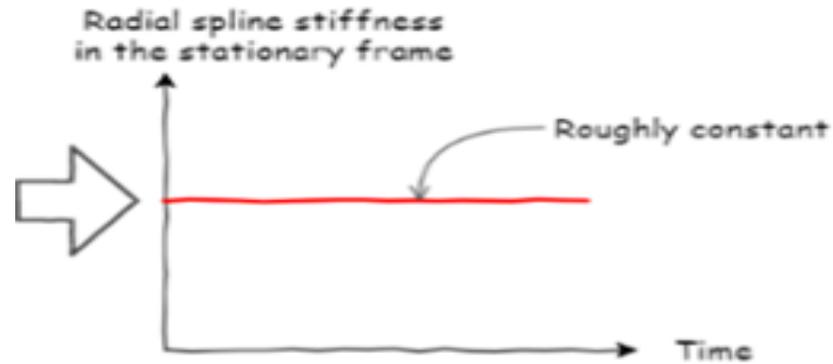
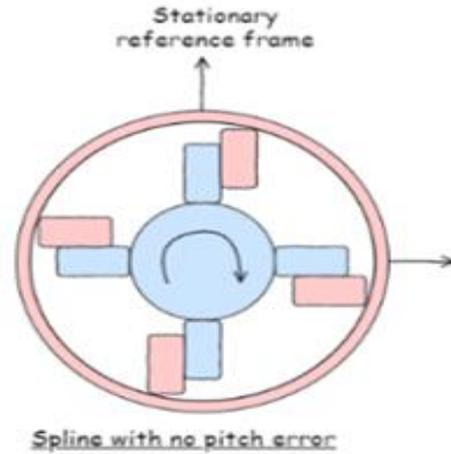
◆ the Trajectory Comparison of test and simulation results



■ e-PT Droning Noise

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◆ Understanding the problem phenomenon



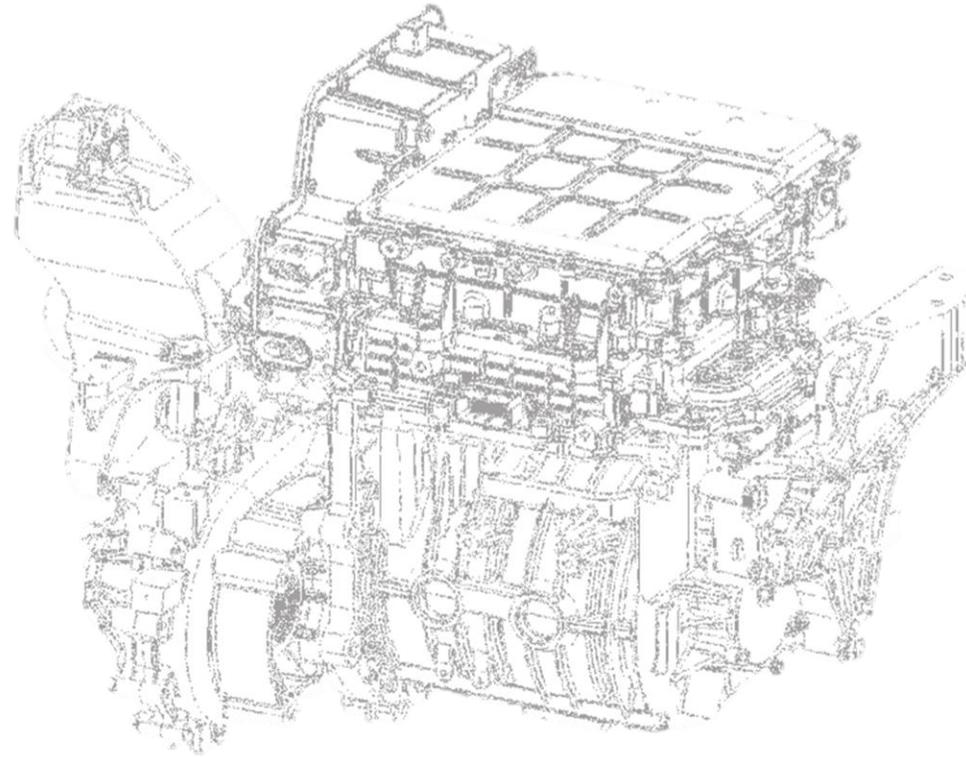
◆ 2nd topic summary and conclusions

- **The droning noise was replicated successfully using a multi-body dynamic model combined with manufacturing errors.**
- **The noise was caused by the spline coupling and was dominated by multiple higher orders to E-motor rotation frequency content.**
- **The two manufacturing tolerances that have the most significant contribution to the droning noise are**
 - **pitch error in the spline coupling**
 - **alignment error between the E-motor and the gearbox shafts.**
- **This part of the study looked at the influence of these errors on the droning noise and explained the underlying cause behind the droning noise.**
- **The cumulative pitch error in the spline coupling was reduced in order to reduce the droning noise and to tighten the tolerances so that the alignment error between the motor and gearbox shaft was reduced.**

- Both parts of this paper have demonstrated **how component level excitation can cause noise emission from an e-PT.**
- Detailed understanding of the **workings of the individual components**, whether they are mechanical or electromagnetic in nature is required as is a **system level model that can predict the transfer of these excitations and resulting noise emission.**
- The combination of a **system level modeling approach**, interfacing software and engineering expertise have enabled the **optimization for noise without compromising previous performance levels or requiring major re-designs.**
- The root-cause of the **unexpected droning noise due to the manufacturing errors** was identified and the countermeasures for noise improvement were established.

NEW THINKING.
NEW POSSIBILITIES.

THANK YOU



11th International Styrian Noise,
Vibration & Harshness Congress
The European Automotive Noise Conference



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