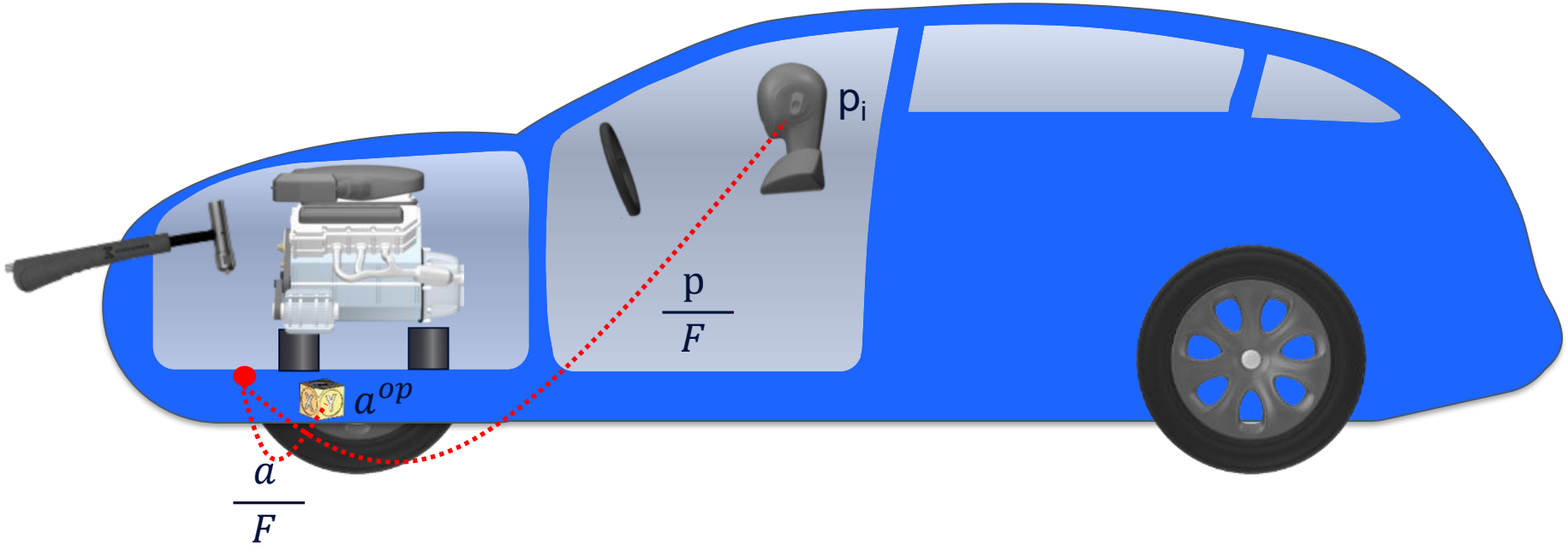
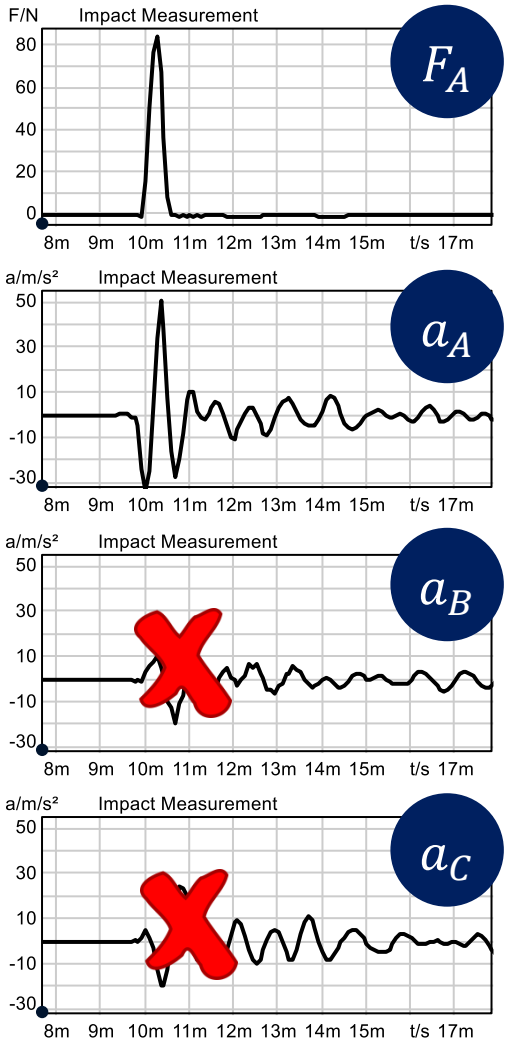
逆矩阵法（简化）





该点的激励力 $$F^{op} = \left[\frac{a}{F}\right]^{-1} * a^{op}$$

该条路径的贡献 $$\mathrm{SPL} = F^{op} * \left[\frac{p}{F}\right]$$

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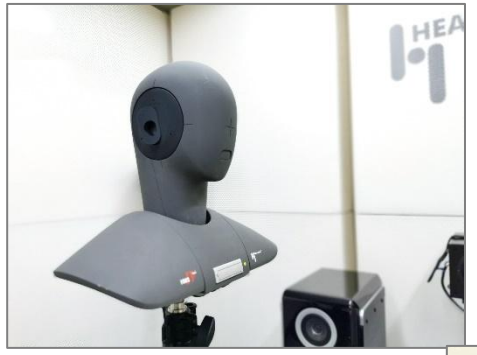
Experiment Information

- 试验相关信息

试验车辆	XXX V-EV两驱版（三元锂电_永磁同步电机）
试验目的	运用BTPA技术精准定位并分析各传递路径贡献量
试验工况	1. 传递函数（结构声与空气声）测试-静态 2. POT工况加速条件的噪声振动测试-动态
试验条件	1. 静态-半消声实验室 2. 动态-带有驱动转毂的整车半消声实验室
试验人员	相关工程师
试验设备	高精度数字双耳采集系统HMS IV，多通道集成数采HEADlab系统 传感器相关等

试验样车-XXXV



高精度数字双耳采集系统
HMS IV

多通道集成数采
HEADlab 系统

HEADlab multi-channel data acquisition system

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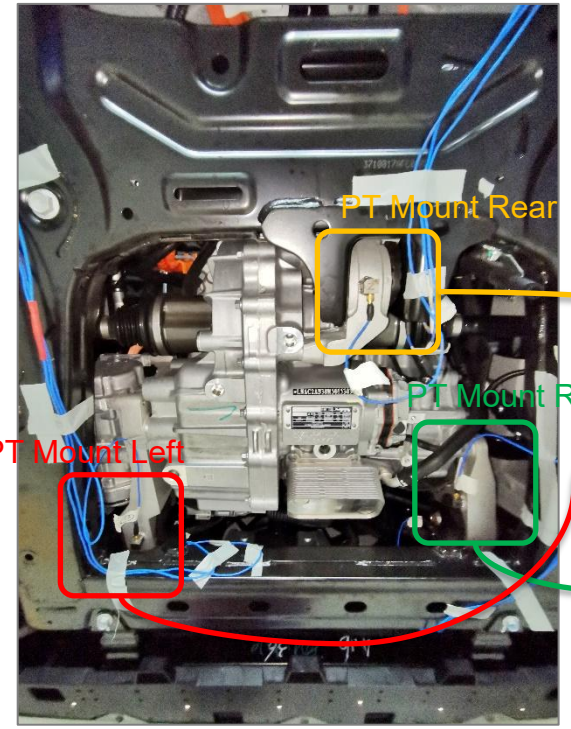
Experiment Information

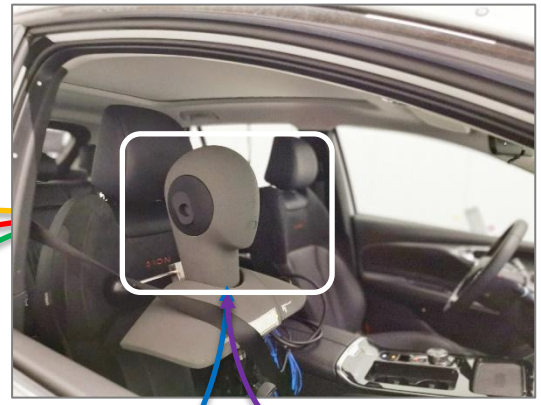
- 路径分解& TPA建模



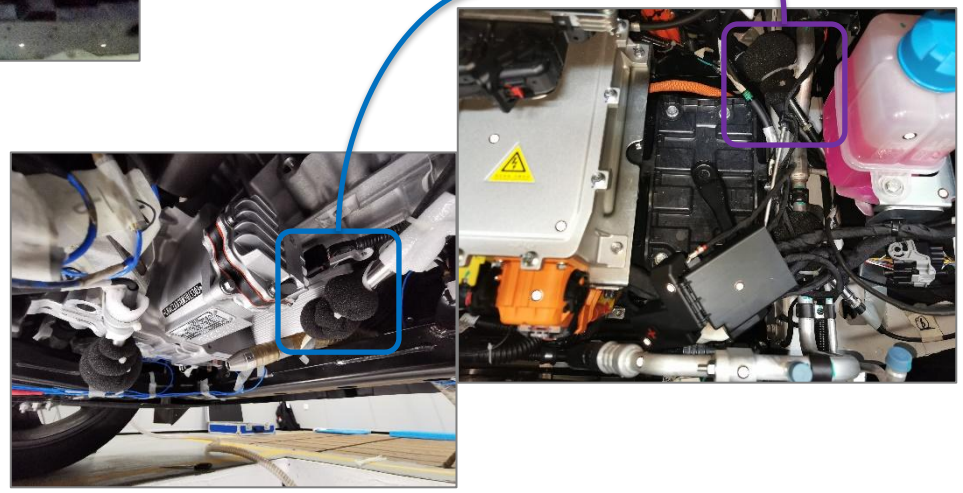
电驱总成悬置系统

结构路径

车内高精度数字双耳采集系统
精准记录来自各路径响应

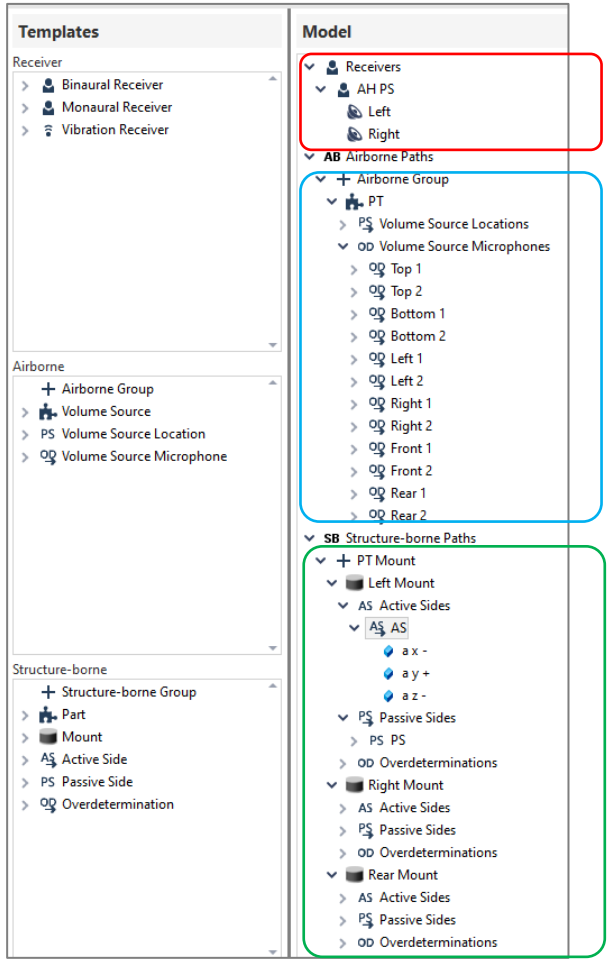


空气
路径



车头方向（左前）

Construction of the TPA model tree



车内接收响应组

空气声组
/动力总成8个麦克风

结构声组
/3个悬置分别布置
加速度

- 此次试验以电驱总成的三点悬置系统为主要贡献量分析路径
- 运用BTPA技术精准定位并分析各传递路径贡献量

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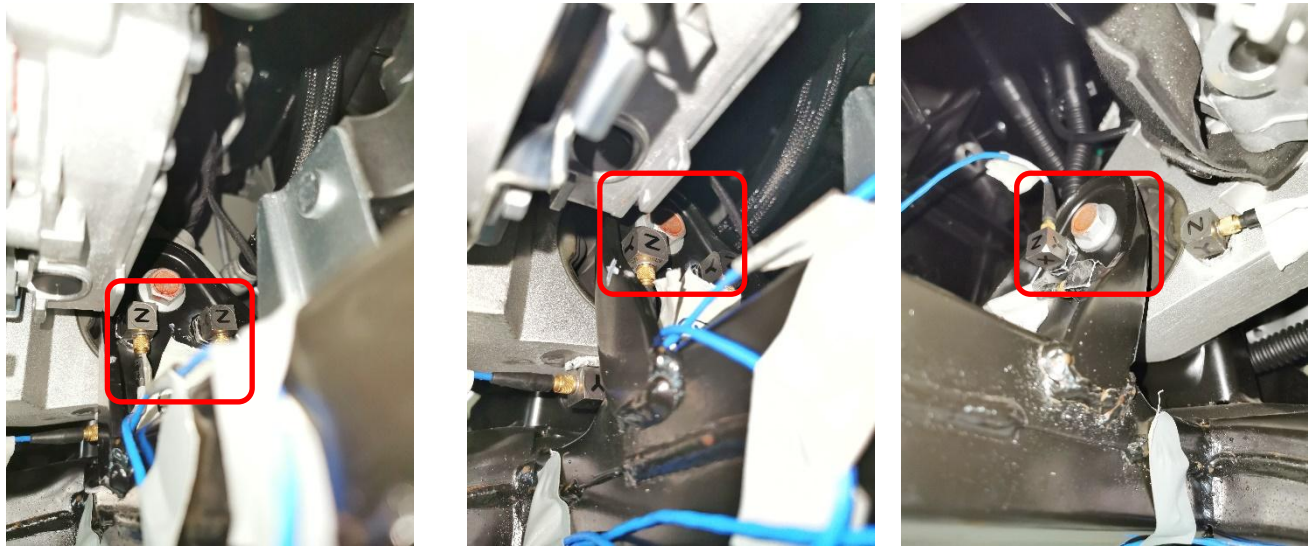
Experiment Information

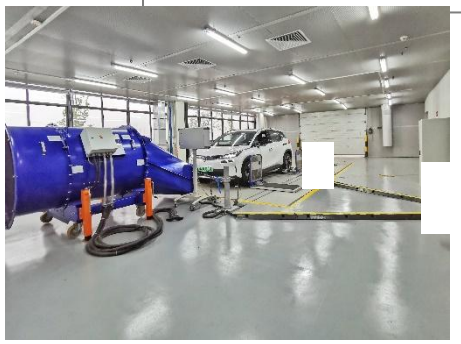
Accelerometers and microphones for structural and airborne paths

- 试验布点& 测试过程



动力总成结构
路径组

静态试验半消声实验室
Semi-anechoic chamber



动态试验整车转毂实验室
Vehicle drum test bench

动力总成空气
路径组

HMS IV high-precision digital binaural system

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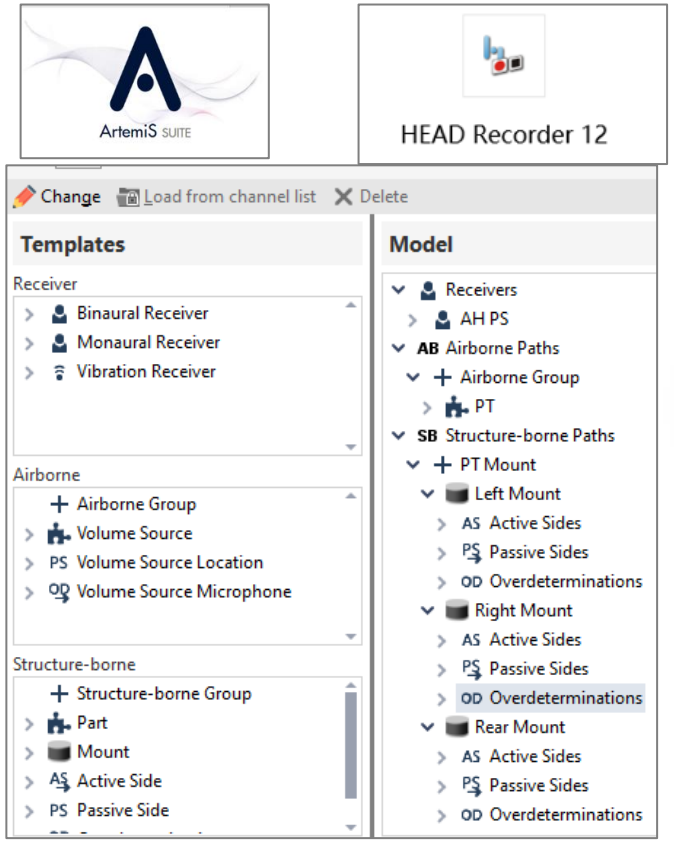
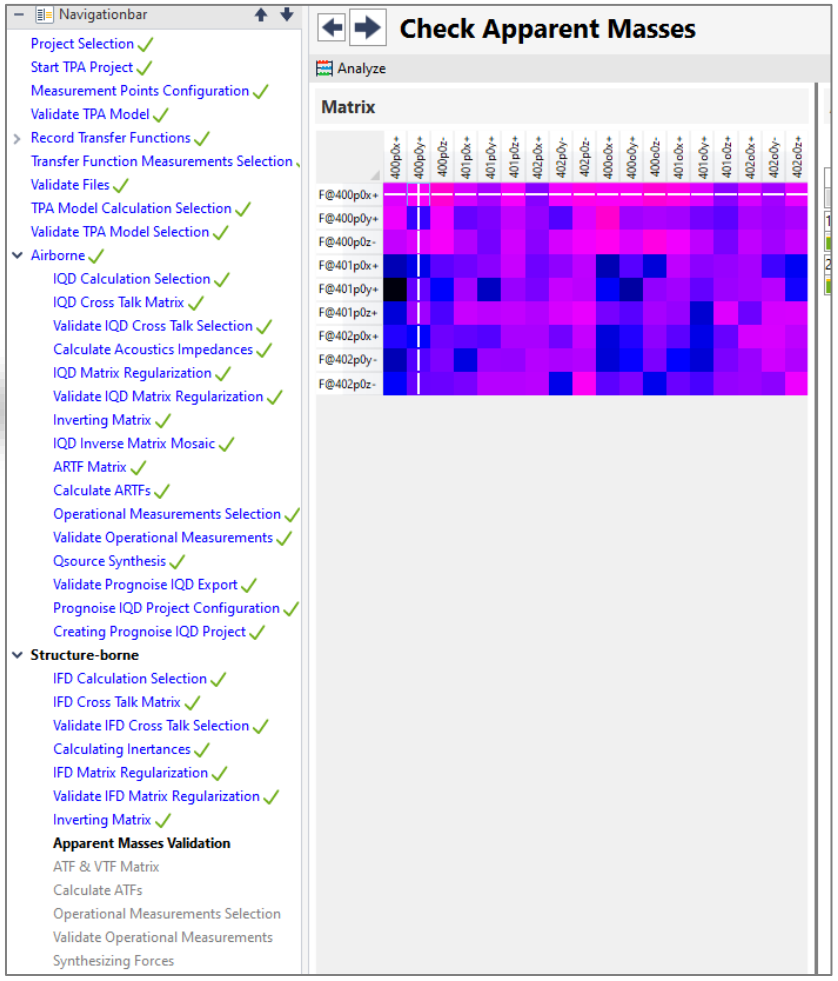
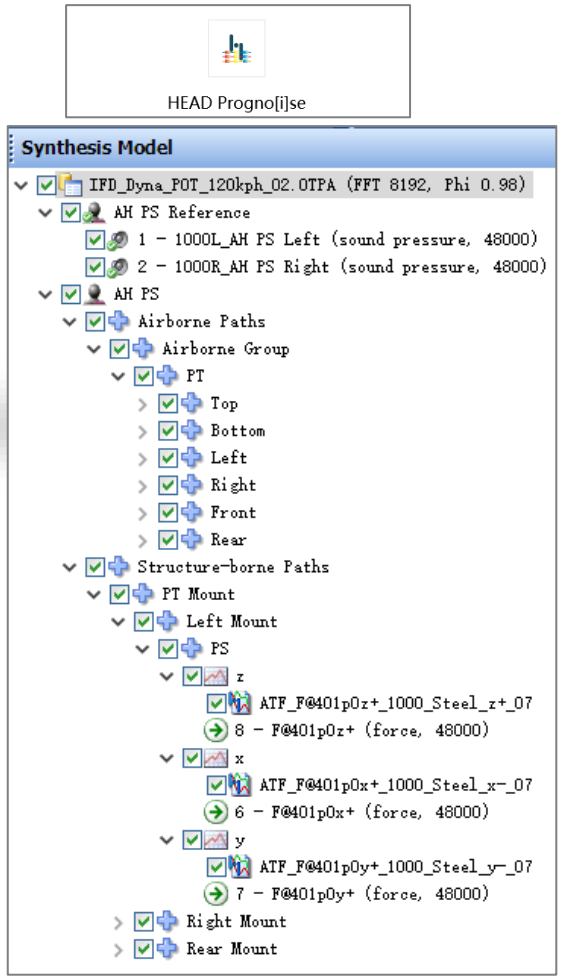
TPA Model Synthesis

- TPA模型拟合

Model Definition /Selection of Interfaces 模型定义/TPA接口选择	Model Synthesis /Processing 模型路径拟合	Transfer Path Analysis and representation 传递路径再现与分析







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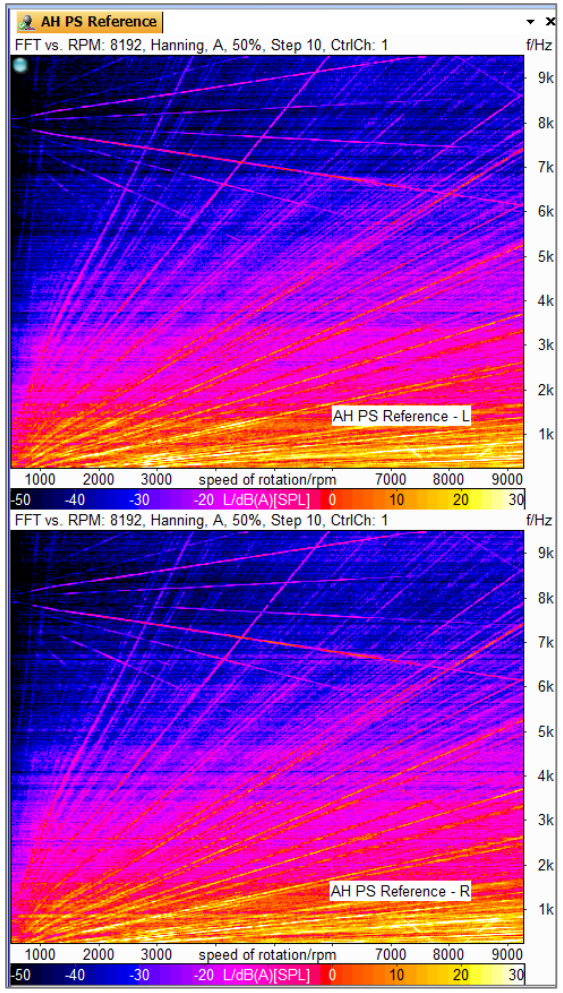
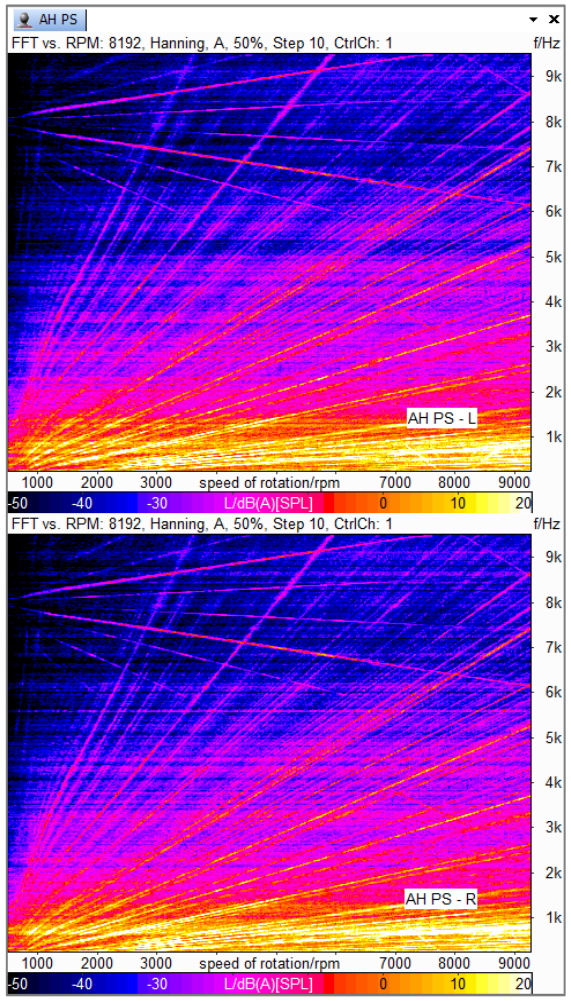
TPA Model Synthesis

- 精度验证Accuracy Verification

实测车内人工头数据



拟合车内人工头数据



- 时域TPA准确拟合且主观可听化；
- 8，16，24和48等电机阶次对比实测和拟合数据几乎完全重合；
- 以8000Hz为中心频率的PMW控制开关频率及其谐波实测与拟合完全重合；
- 时域回放可听化主观感受与客观数据结合。

The TPA model shows excellent agreement with measurements:

•Time-domain signals are accurately reconstructed and audible

•Motor orders (8, 16, 24, 48) match closely between measurement and synthesis

•PWM switching frequency (~8000 Hz) and harmonics show near-perfect overlap

•Subjective listening results are consistent with objective metrics

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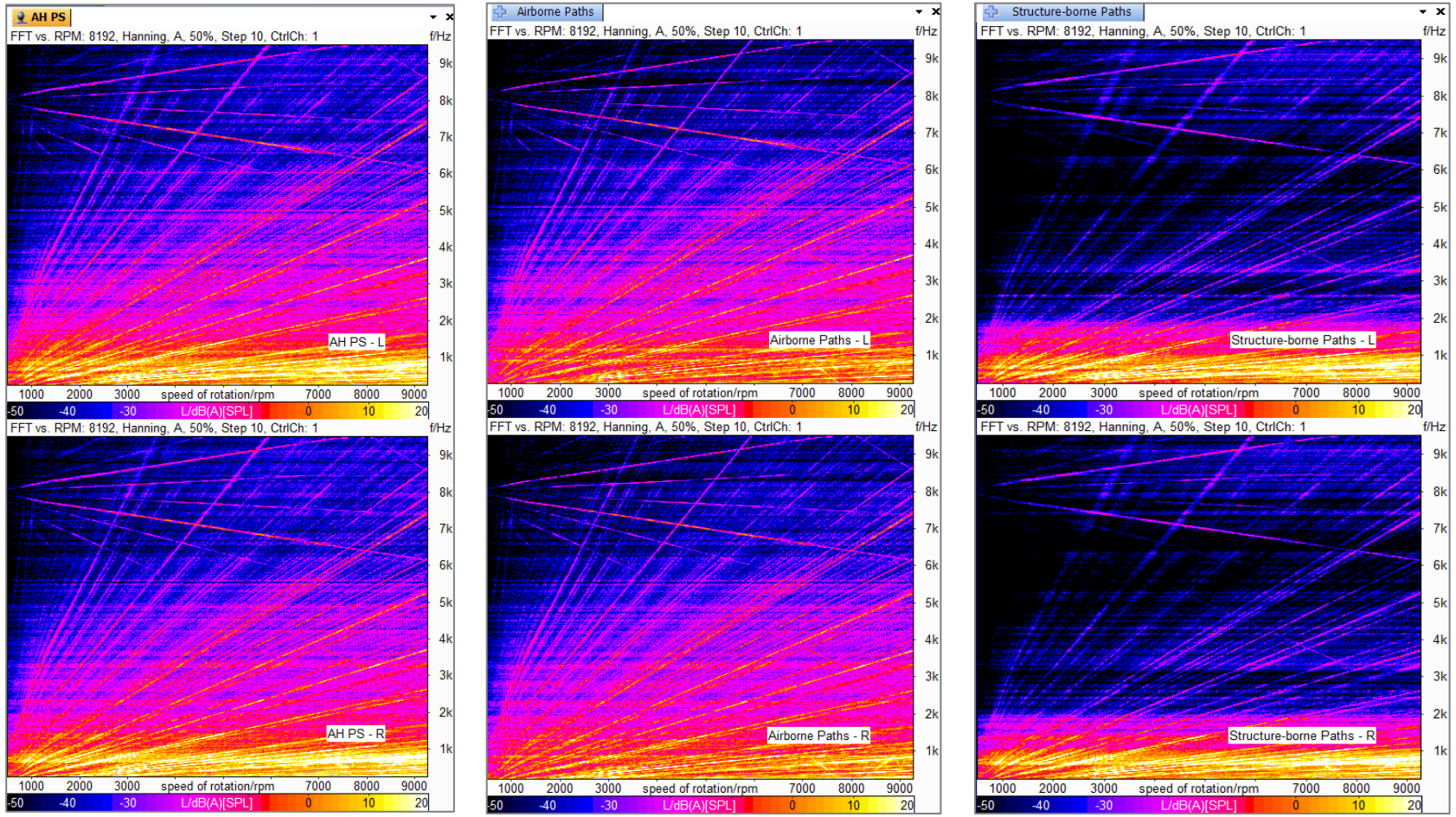
Transfer Path Analysis

- 空气与结构拆分/Airborne and Structure-Borne Contribution

空气声与结构声贡献量分析



总量级/overall　　空气声/AB　　结构声/SB

- 空气声占比主要在中高频，包括电机及其谐波24，48和96等阶次
- 结构声占比主要在1KHz以下成分
- PWM控制器开关频率及其谐波阶次在空气和结构路径均有贡献

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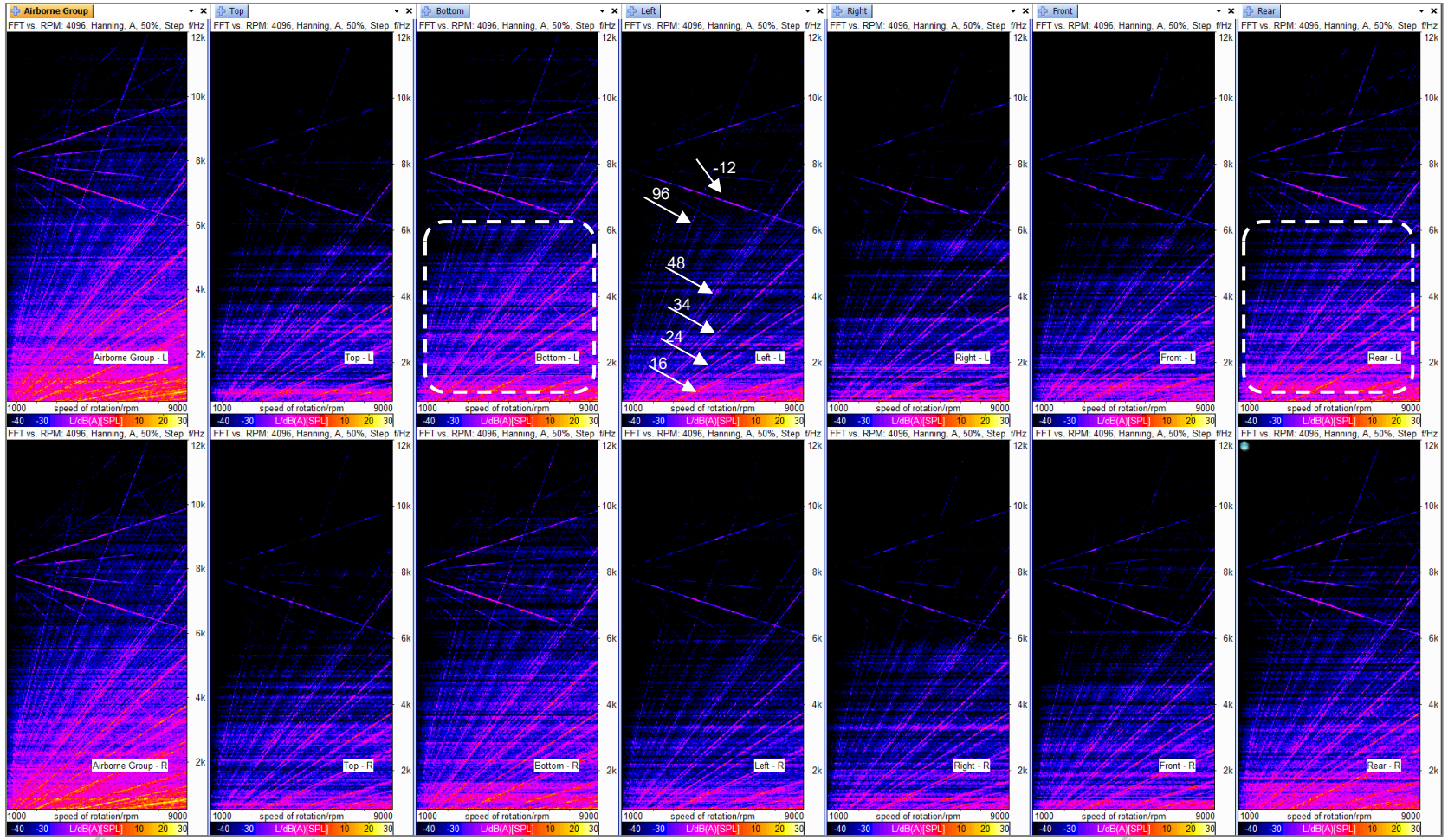
Transfer Path Analysis

- 空气组贡献量/Airborne Group

空气声贡献量路径分析/Airborne Path



- 24、48等电机阶次贡献占比来自下表面和后表面较大；
- PWM是-12阶次的主要贡献路径也来源动总的下表面和后表面

Key findings:

•Significant contributions from **bottom and rear surfaces** of the powertrain

•Motor orders 24 and 48 show strong airborne radiation

•PWM -12 order mainly originates from bottom and rear airborne paths

Color-band analysis clearly identifies dominant airborne radiation locations across speed ranges.

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Transfer Path Analysis

响应大

- *传递函数大？*

- *激励大？*

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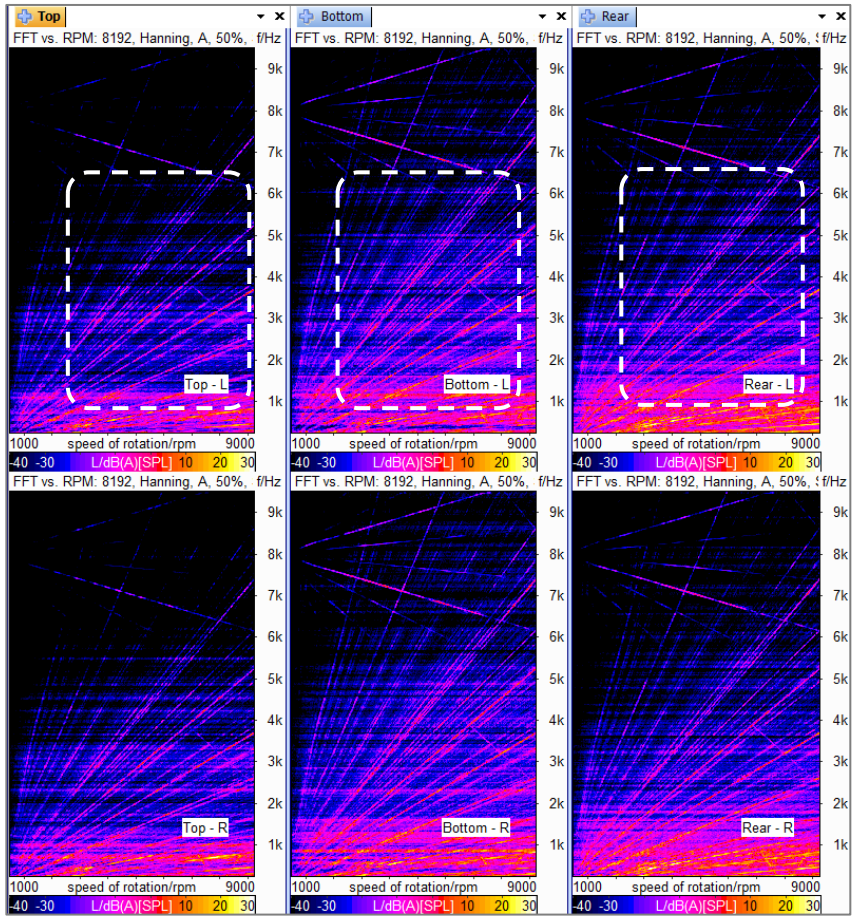
Transfer Path Analysis

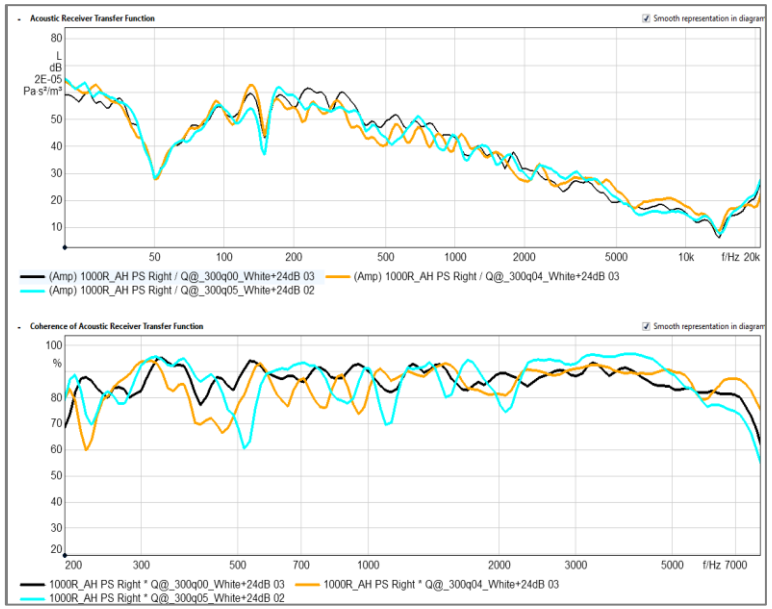
- 空气声下和后表面

响应

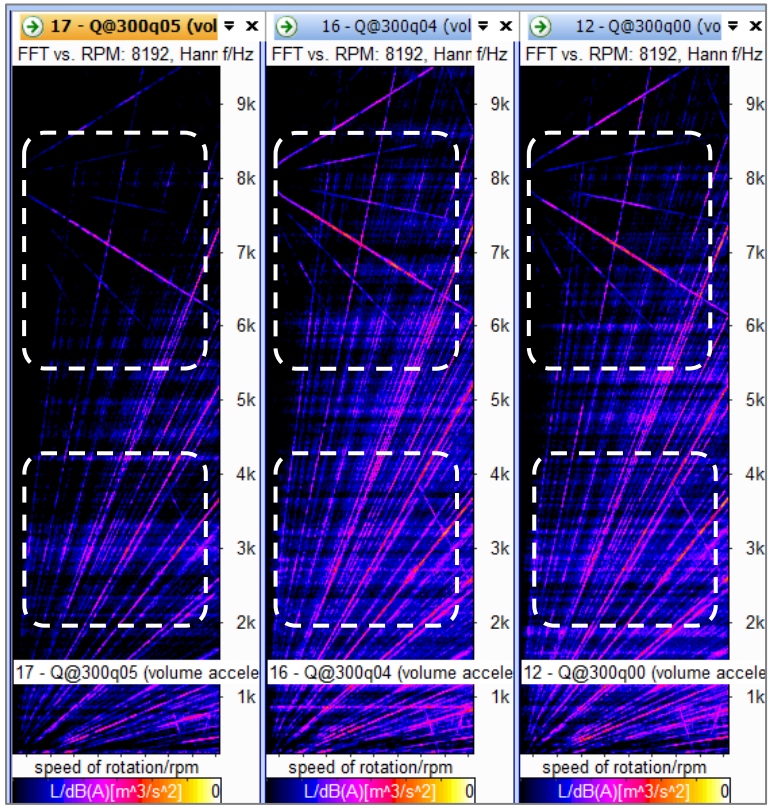


选取上表面麦克风作为参考

传递函数



激励

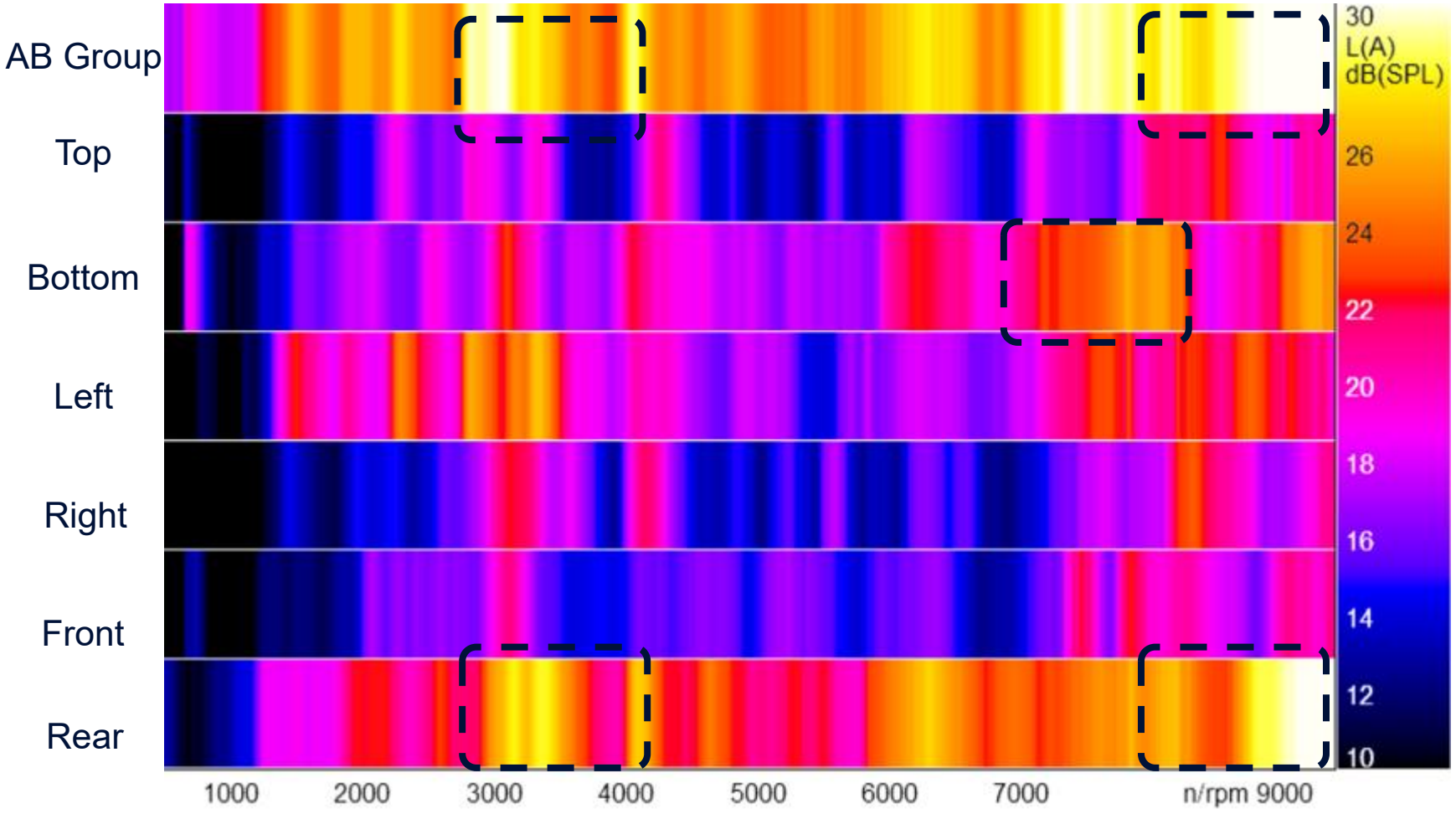


激励 > 传递函数

Transfer Path Analysis

- 空气组贡献量排序/ Colorband_ Left

空气声贡献量路径分析定位



- 通过Colorband 清晰定位各个转速下对应空气声的位置

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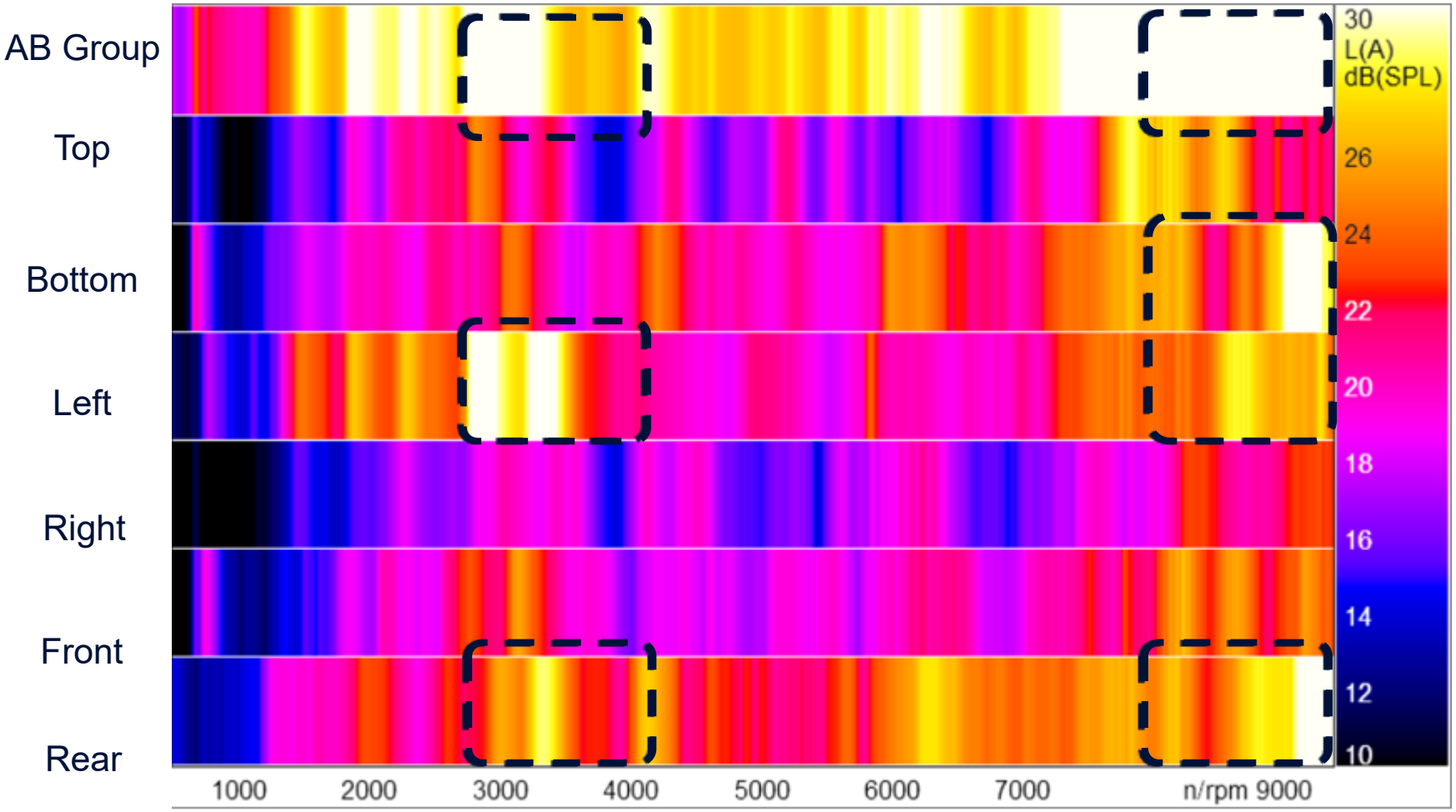
Transfer Path Analysis

- 空气组贡献量排序/ Colorband_ Right

空气声贡献量路径分析定位



- 通过Colorband 清晰定位各个转速下对应空气声的位置

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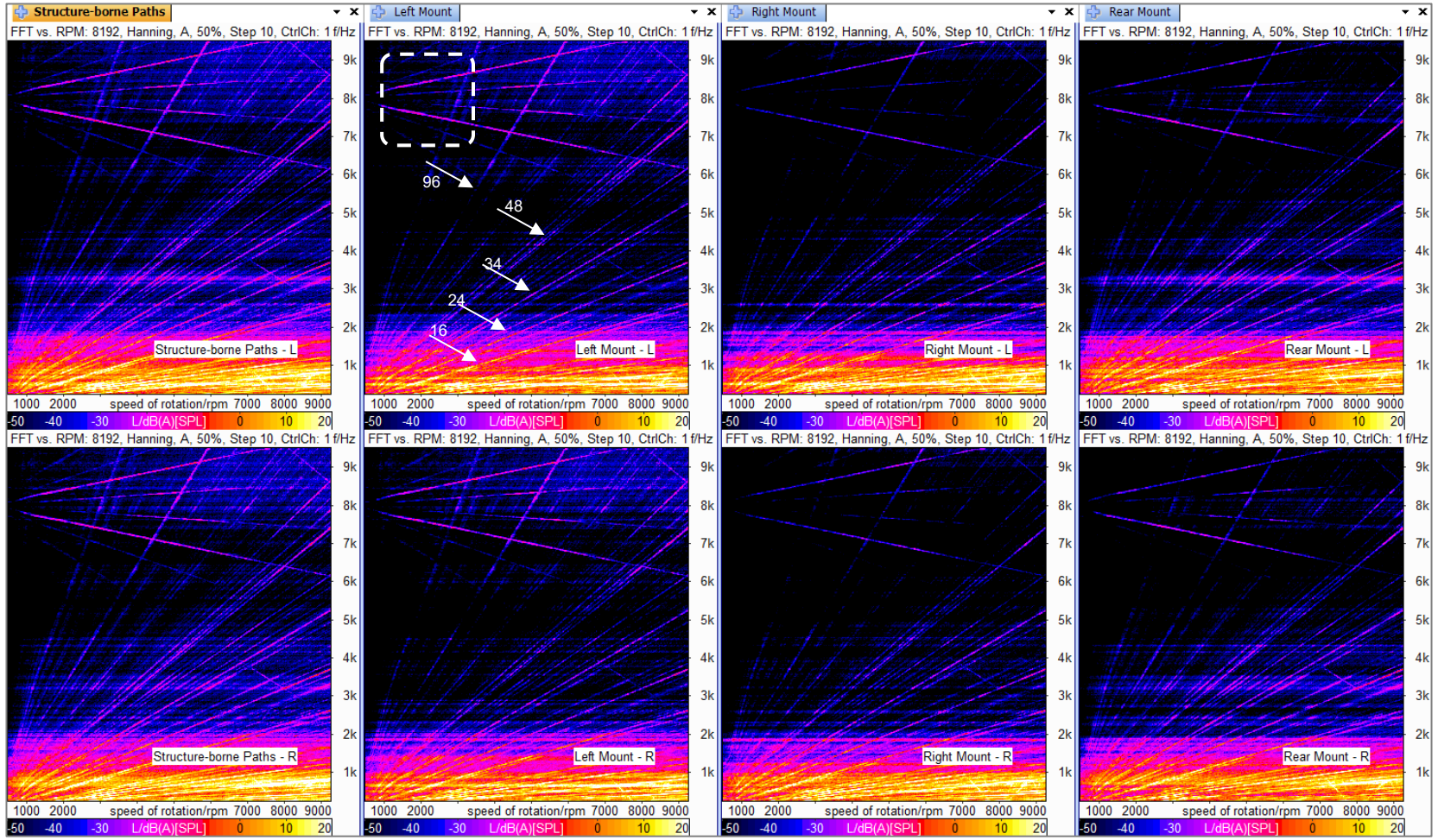
Transfer Path Analysis

- 结构组贡献量SB Group

结构声贡献量路径分析



- 1000Hz以下的贡献主要以结构声为主;
- 16，24和48阶次在4000Hz以下左悬置和后悬置的阶次贡献突出;
- 以8000Hz为中心频率的PWM控制器开关及其谐波在左悬置贡献突出，以±12阶次最明显

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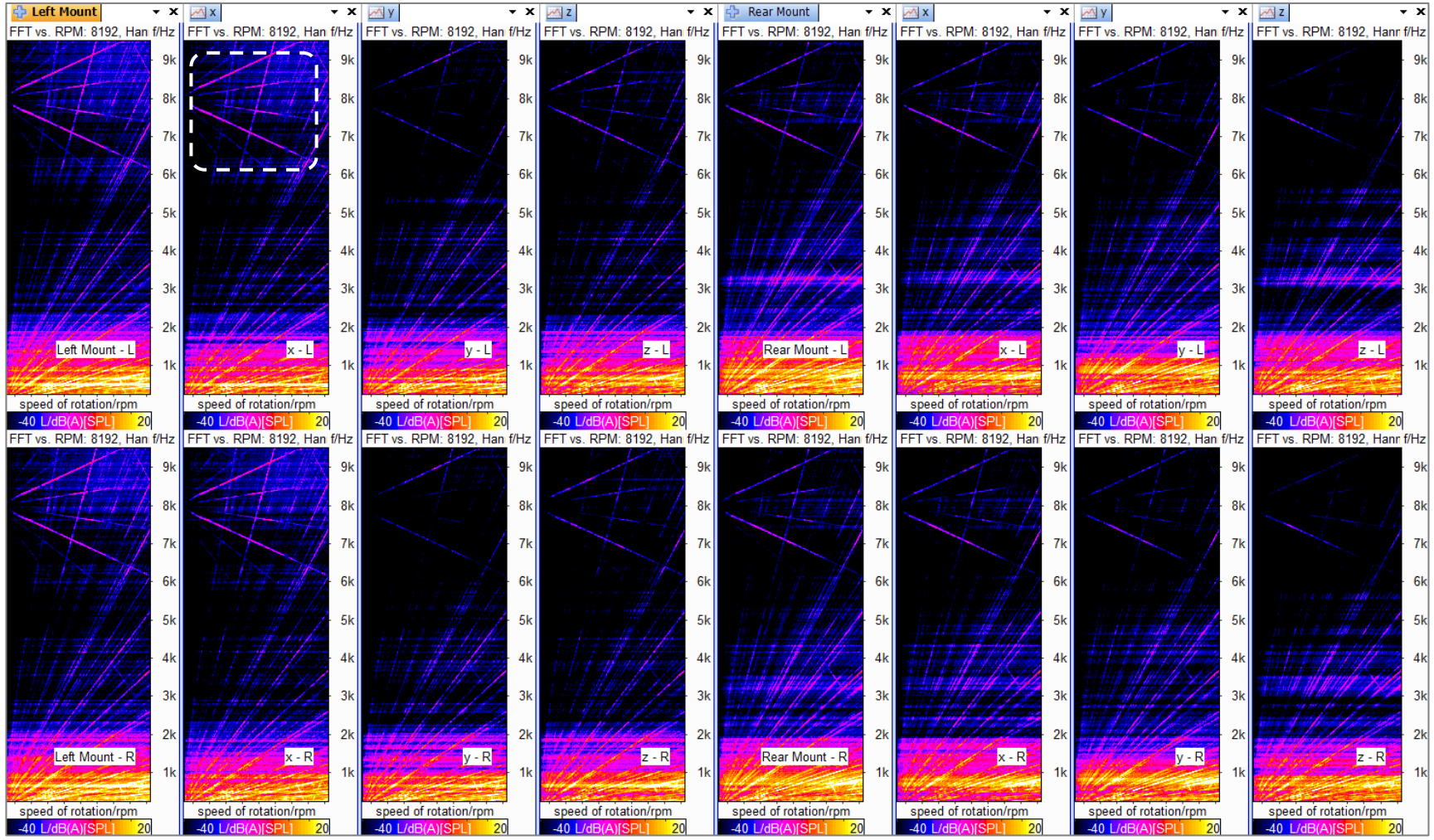
Transfer Path Analysis

- 结构组贡献量/ PT Left+Rear

结构声贡献量路径分析



- 左悬置X方向电机96阶和PWM±4，±12阶次贡献量突出

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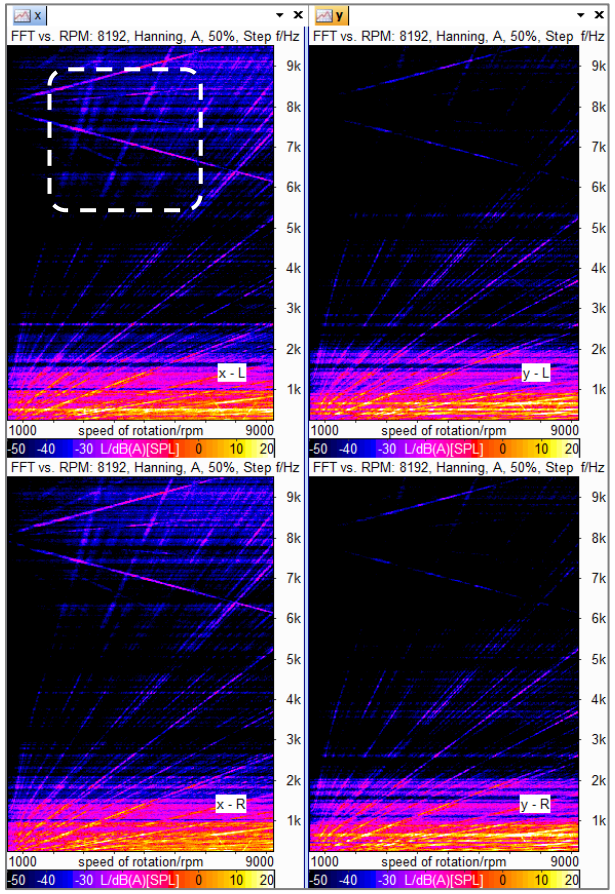
Transfer Path Analysis

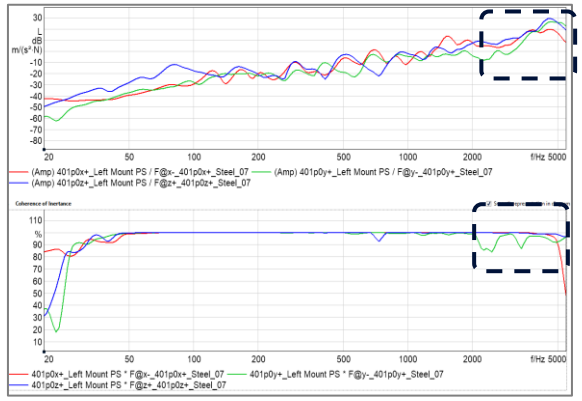
- 左悬置PWM阶次

响应

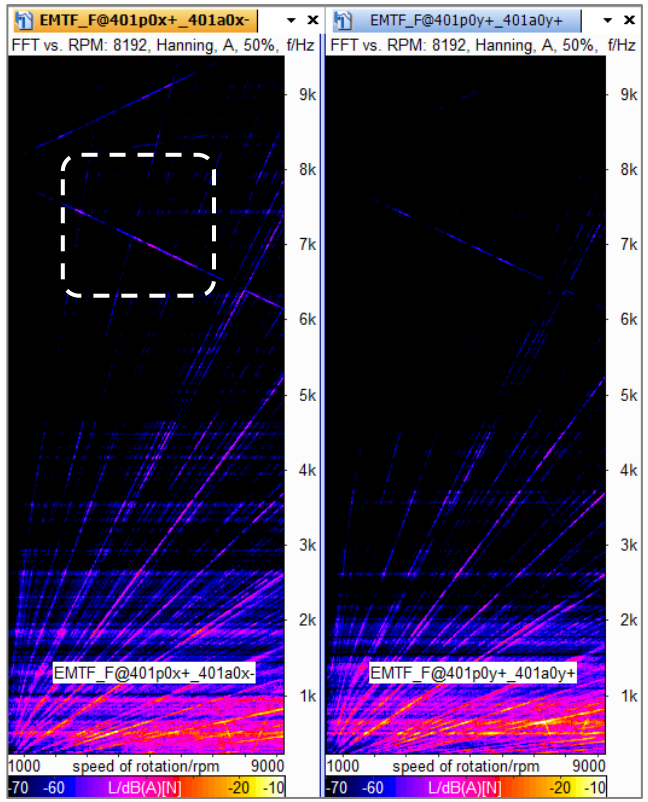


选取Y方向作为参考

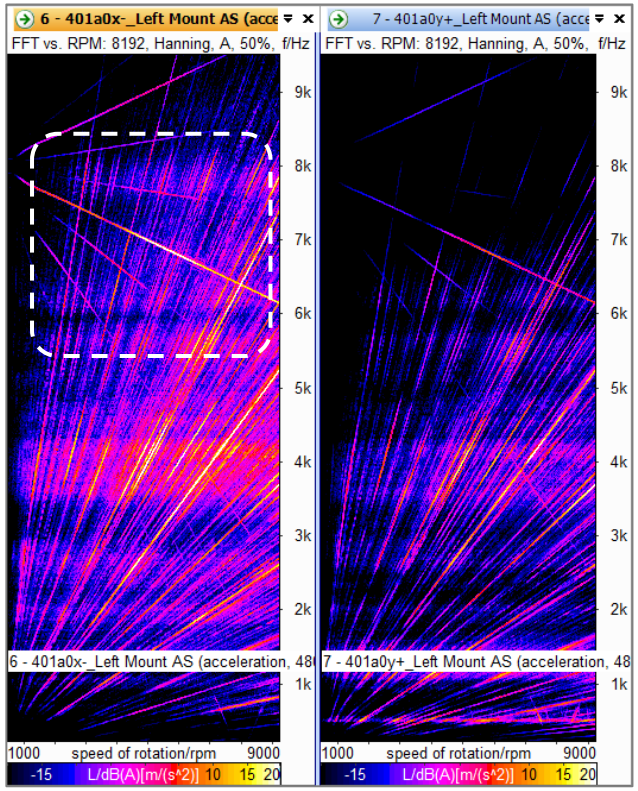
传函



隔振率



激励



激励＞隔振率＞传递函数

Directional analysis confirms:

•Excitation level > Isolation performance > Transfer function magnitude

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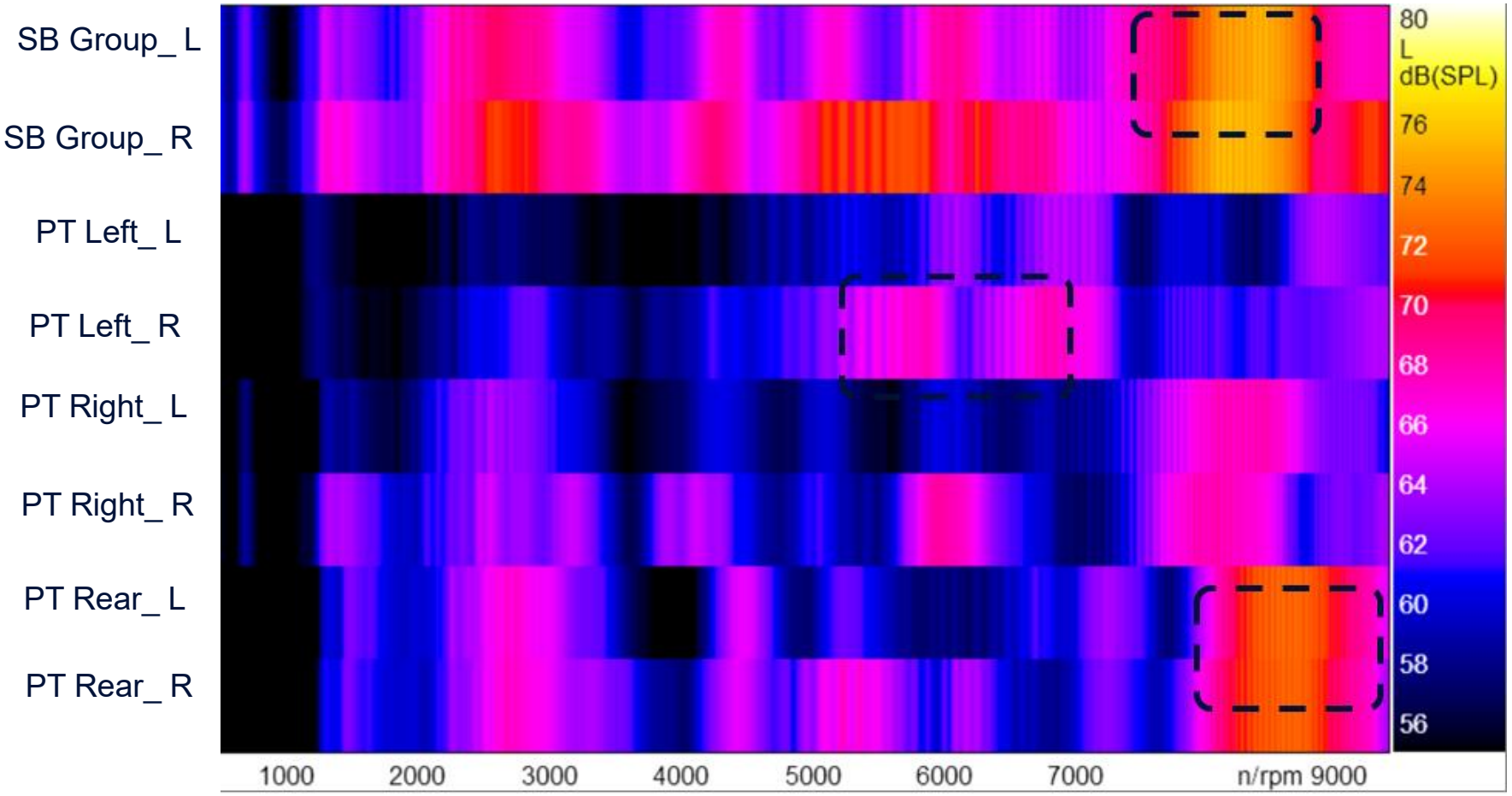
Transfer Path Analysis

- 结构组贡献量排序/ Colorband

结构声贡献量路径分析定位



- 通过Colorband 清晰定位各个转速下对应结构声的位置

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Transfer Path Analysis

- 虚拟需改与预测

1）基于仿真数据运行数据的振动噪声或传函修改预测

2）基于台架数据与整车结合，替换不同的源与传函，缩短整车开发周期和提高验证效率

3）基于工程试验数据的修改预测，用于指导并提高整车和零部件的实车验证效率

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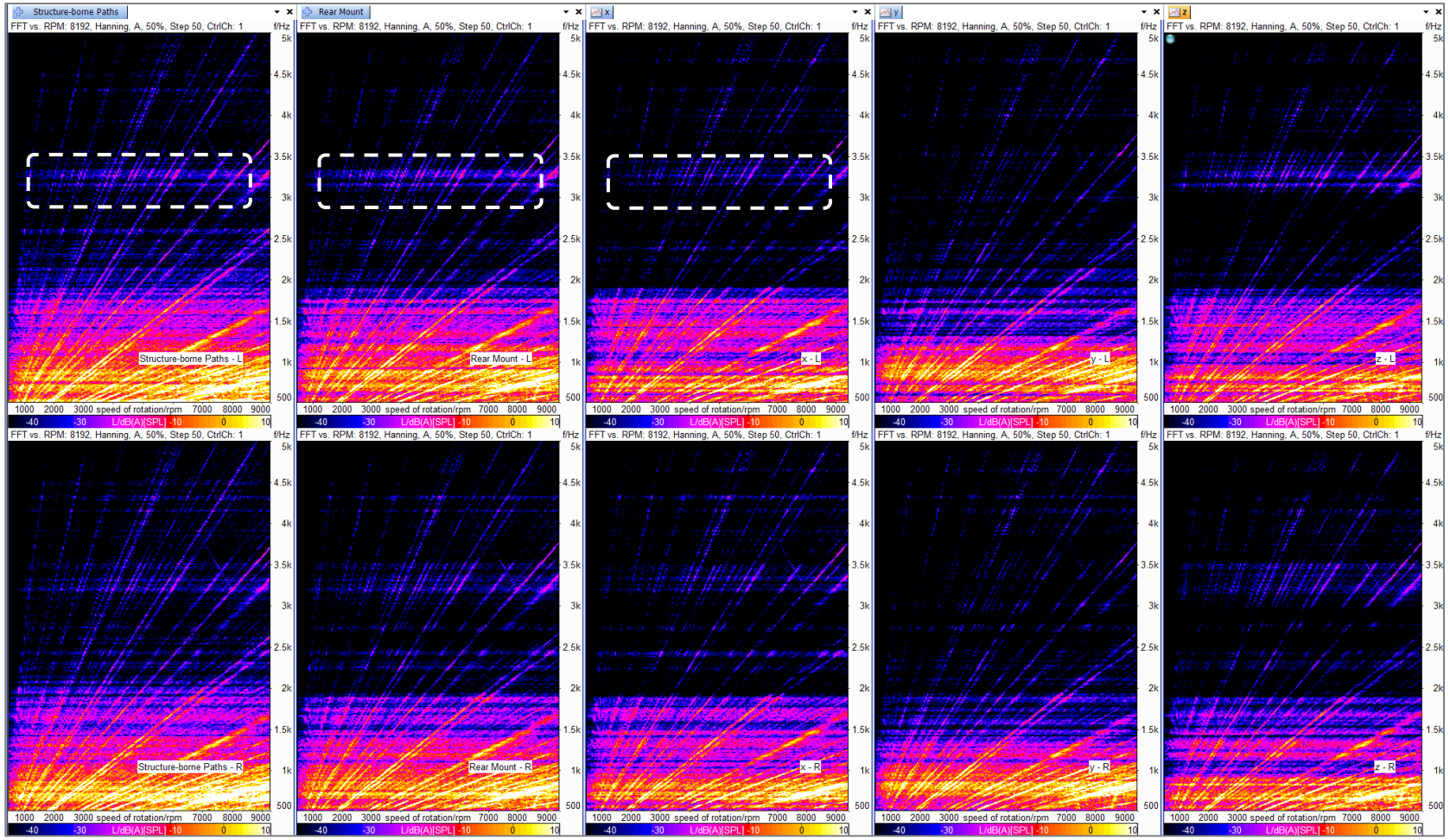
Transfer Path Analysis

- 案例分析/ 3200Hz 共振带



- 3200Hz共振带下导致整个阶贡献量增强

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Transfer Path Analysis

- 案例分析/ 3200Hz 共振带

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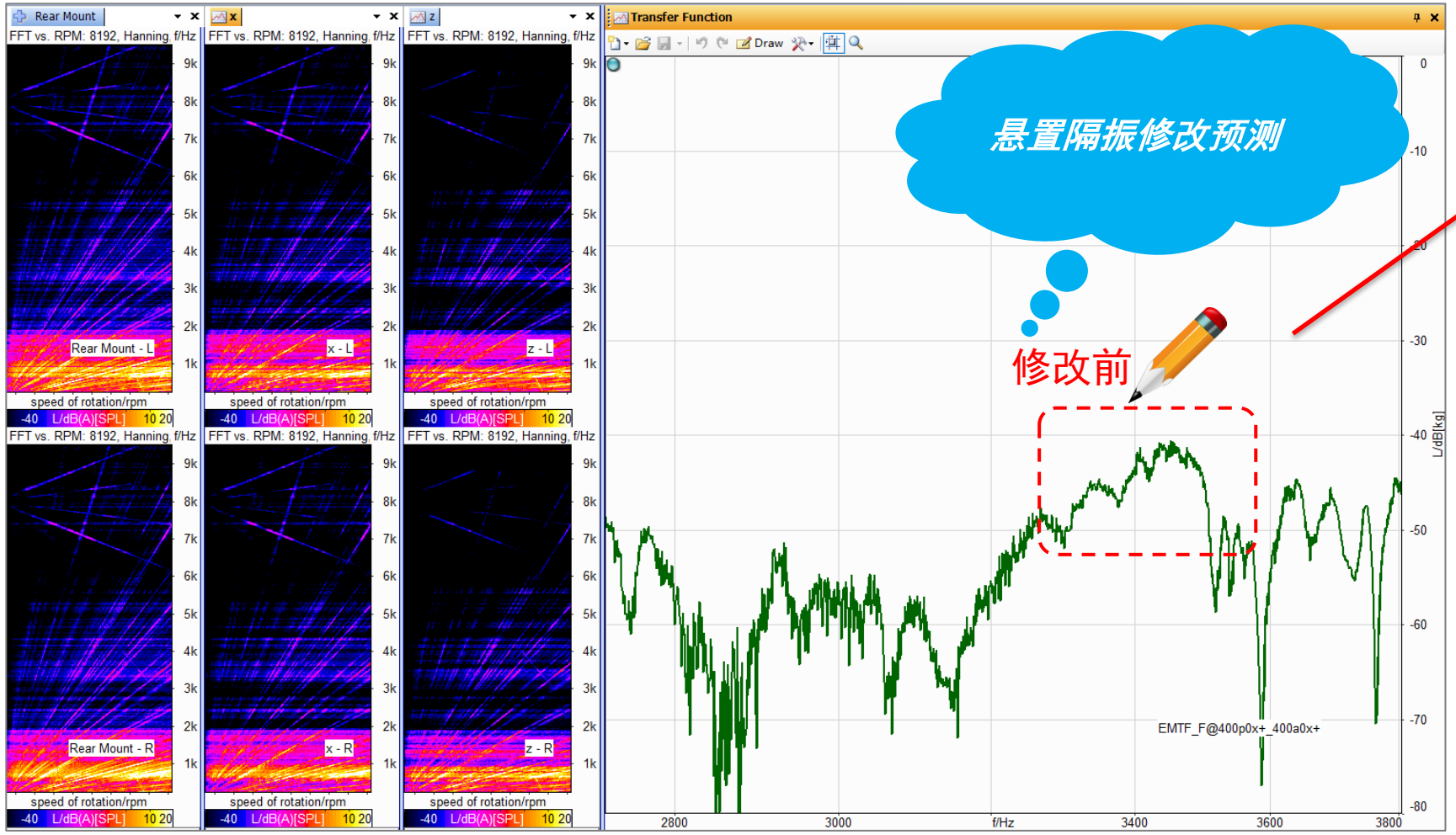
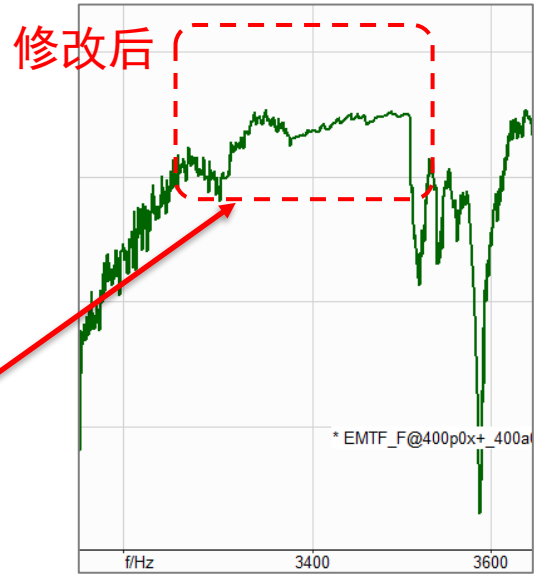
Transfer Path Analysis

- 案例分析/ 3200Hz 共振带





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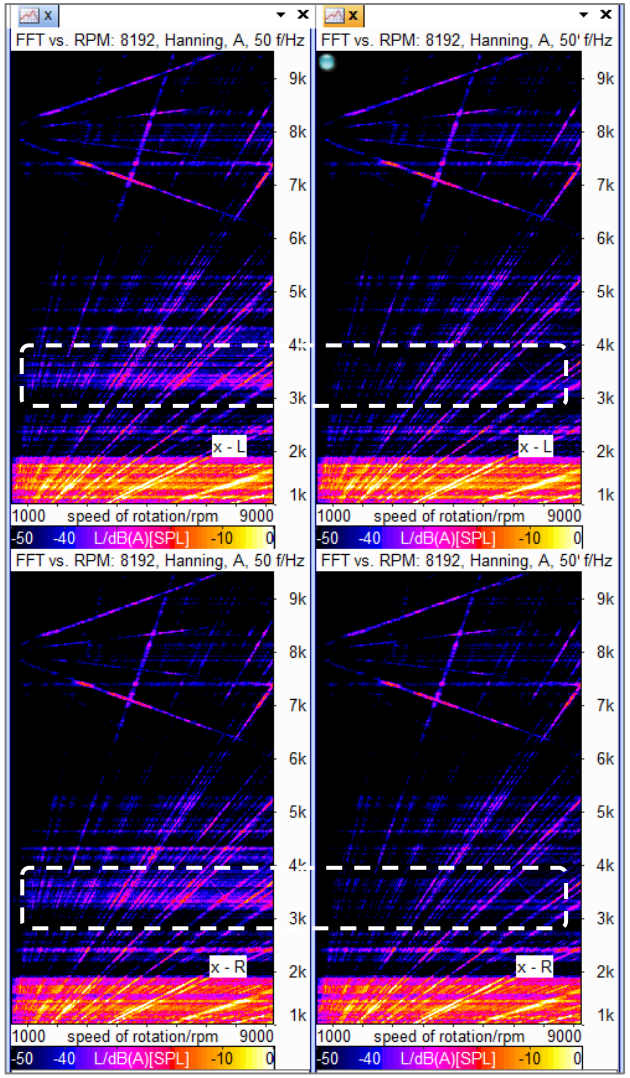
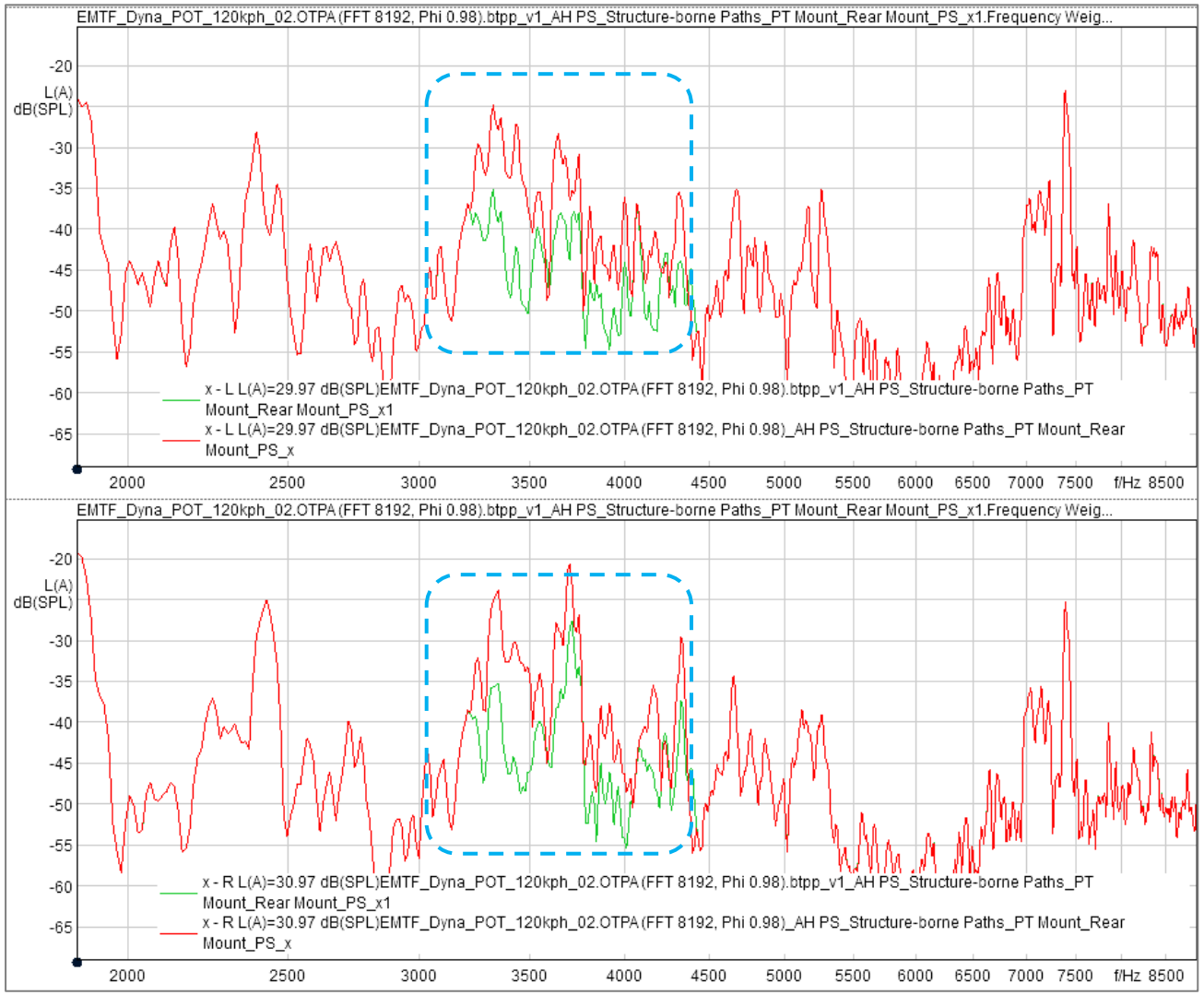
Transfer Path Analysis

- 案例分析/ 3200Hz 共振带



3D修改前后X项差异



2D修改前后X项差异

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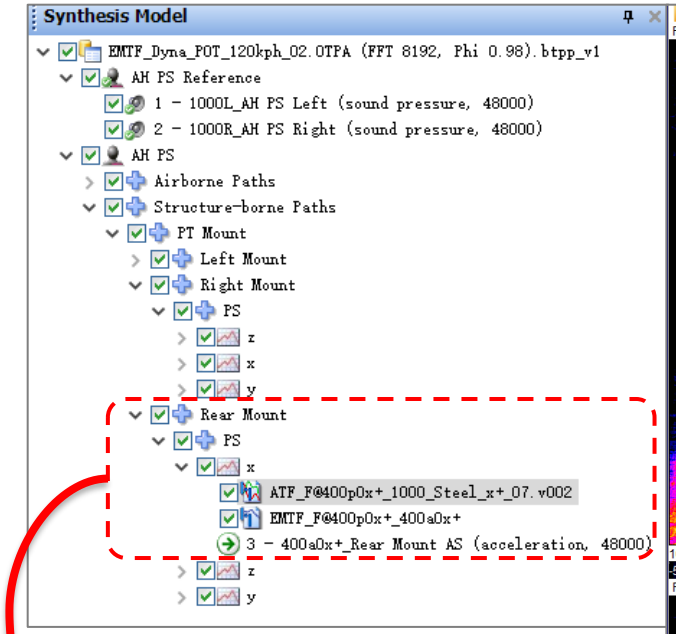
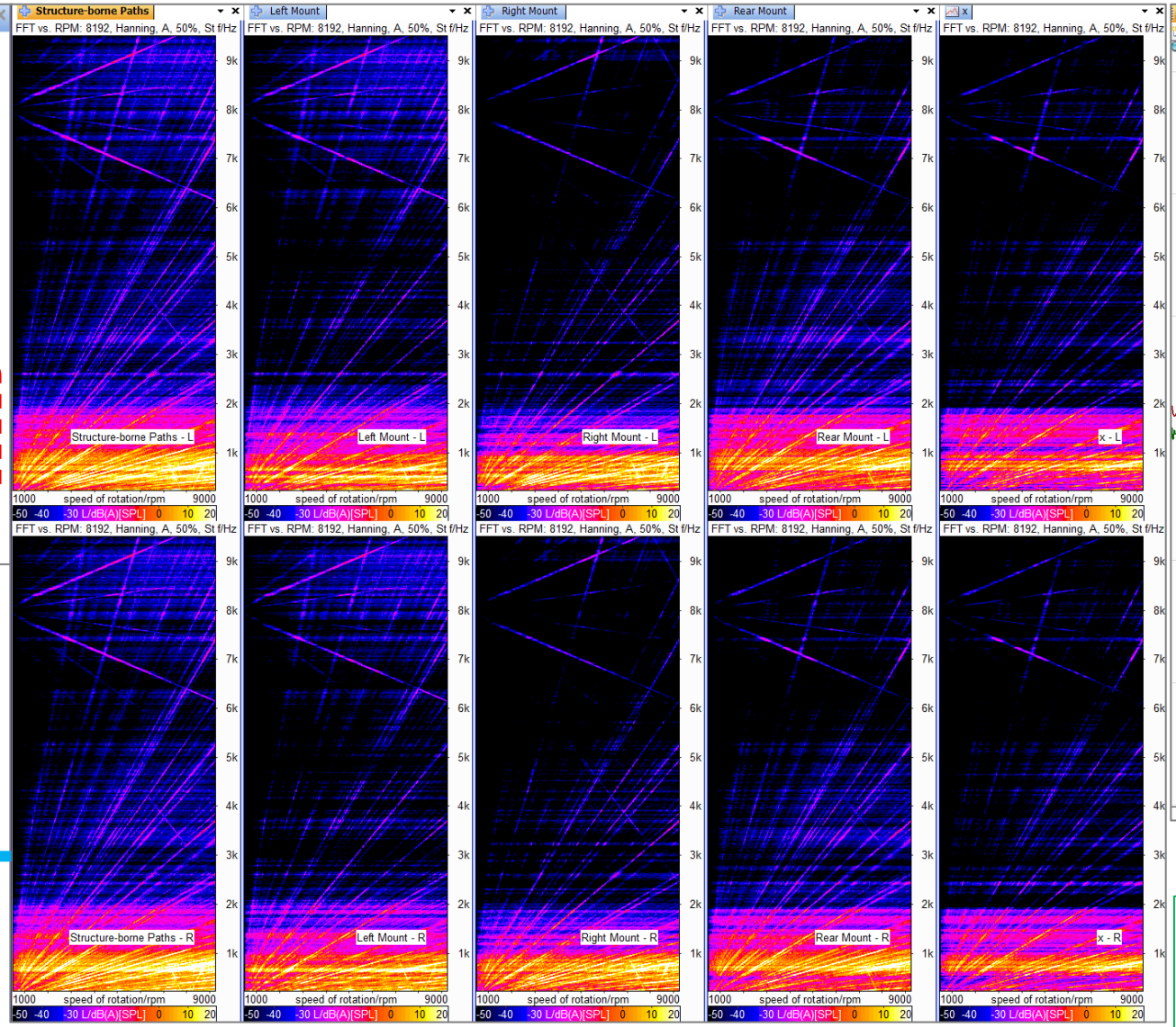
EMTF

可视化路径模型树



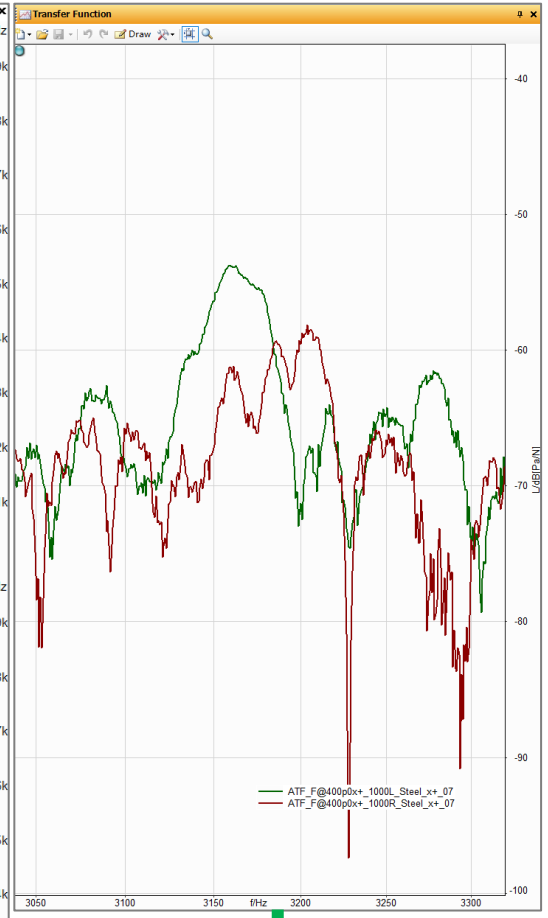
- ATF传函
- EMTF悬置传递特性
- 主动侧激励

可听化路径分解



- 可视化路径分解
- 时域可听化主观评估
- 结合虚拟改进实时显示

虚拟改进与预测传函



- ATF虚拟修改预测
- EMTF悬置特性修改预测
- 不同传函与特性切换

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