太原理工大学
TAIYUAN UNIVERSITY OF TECHNOLOGY

基于振动信号的柴油机NOx排放虚拟传感研究

Vibration Based Virtual Sensing of Nitrogen Oxide Emission in CI Engines

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提纲 outline

背景与意义

- Background and significance

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- Correspondence between emissions and vibration

试验设计与2D滤波器

- Design of experiments- 2D filter

NOx虚拟传感

- Virtual sensing of NOx emissions

背景与意义 Background and significance

- In addition to solid legal basis and strong regulatory authority, emissions monitoring techniques are key elements for achieving ever strict environmental requirements.

除了坚实的法规和严格的监管，有效的排放监测技术是实现日益严格的环境要求的关键要素。

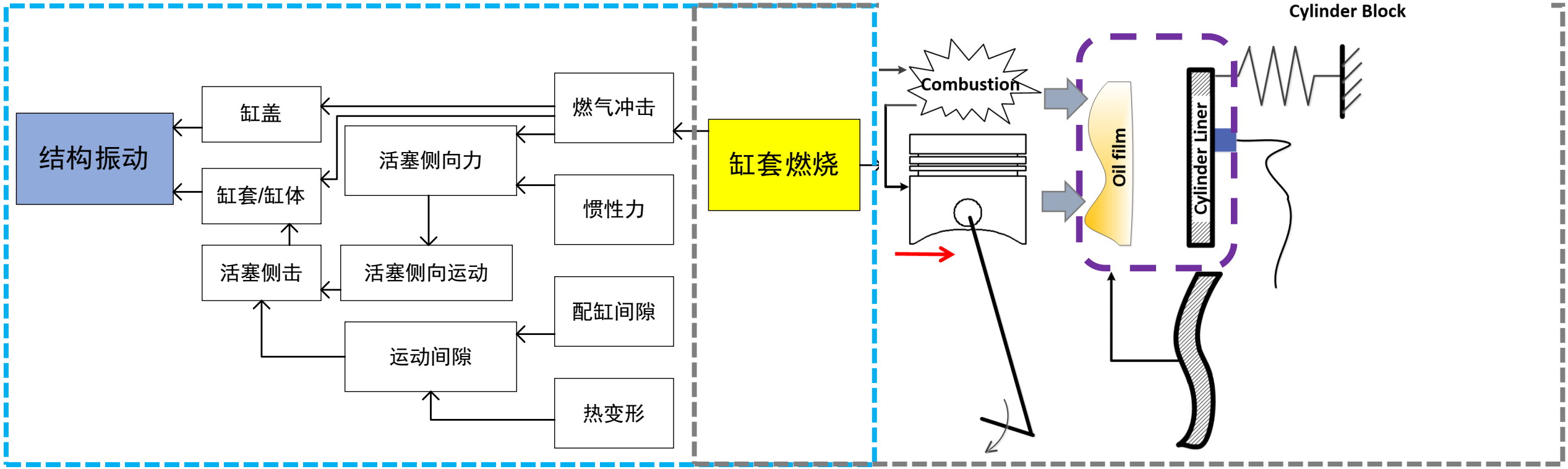
- However, most of existing portable emission measurement system (PEMS) are expensive and bulky, making it impractical to roll out to the vehicle market.

但是，大多数现有的排放物测量系统（PEMS）昂贵且笨重，因此无法大范围推广到汽车市场。

- Based on correspondence between vibration response and emissions, it is possible to achieve cost-effective non-intrusive on-line monitoring of engine in real-driving emissions (RDE)

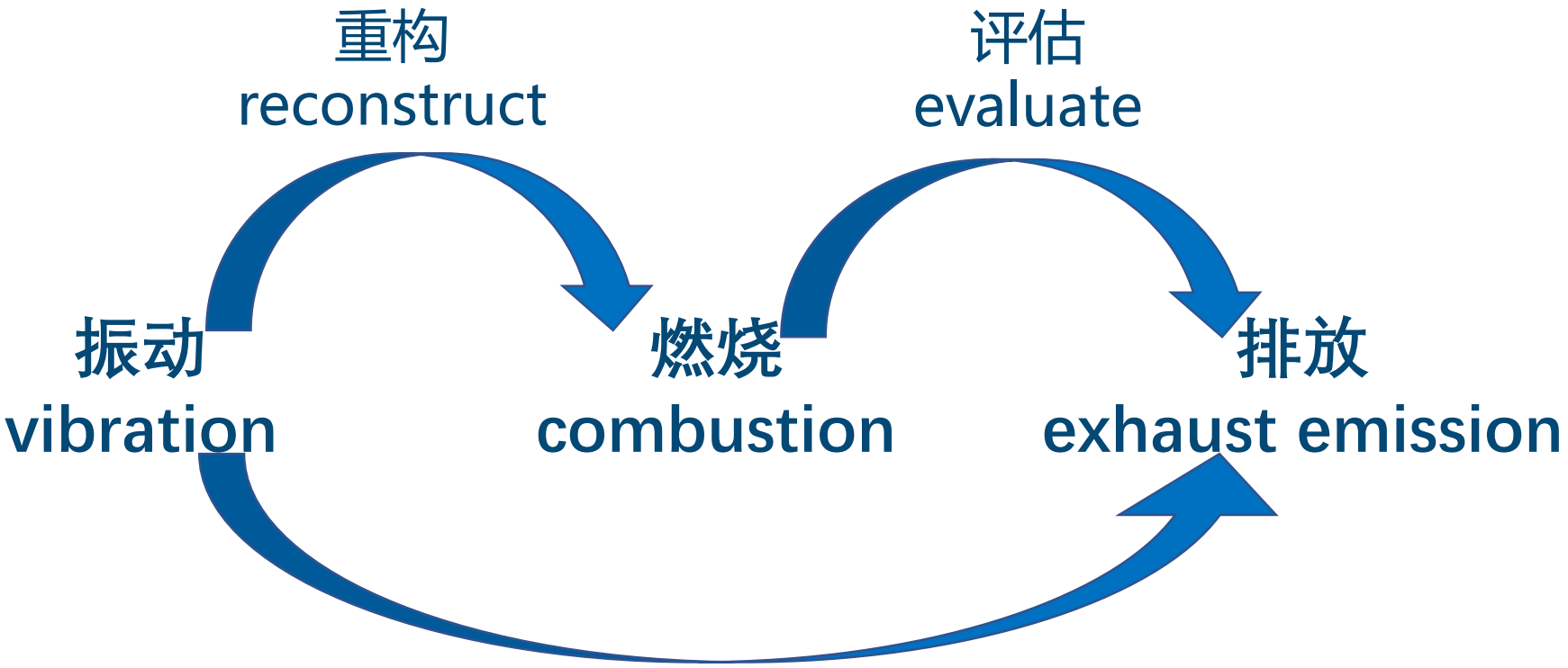
基于结构振动响应和NOx排放之间的对应关系，有望实现对发动机实际行驶排放（RDE）进行经济高效的非侵入式在线监测。

排放与振动的关联 Correspondence between emissions and vibration



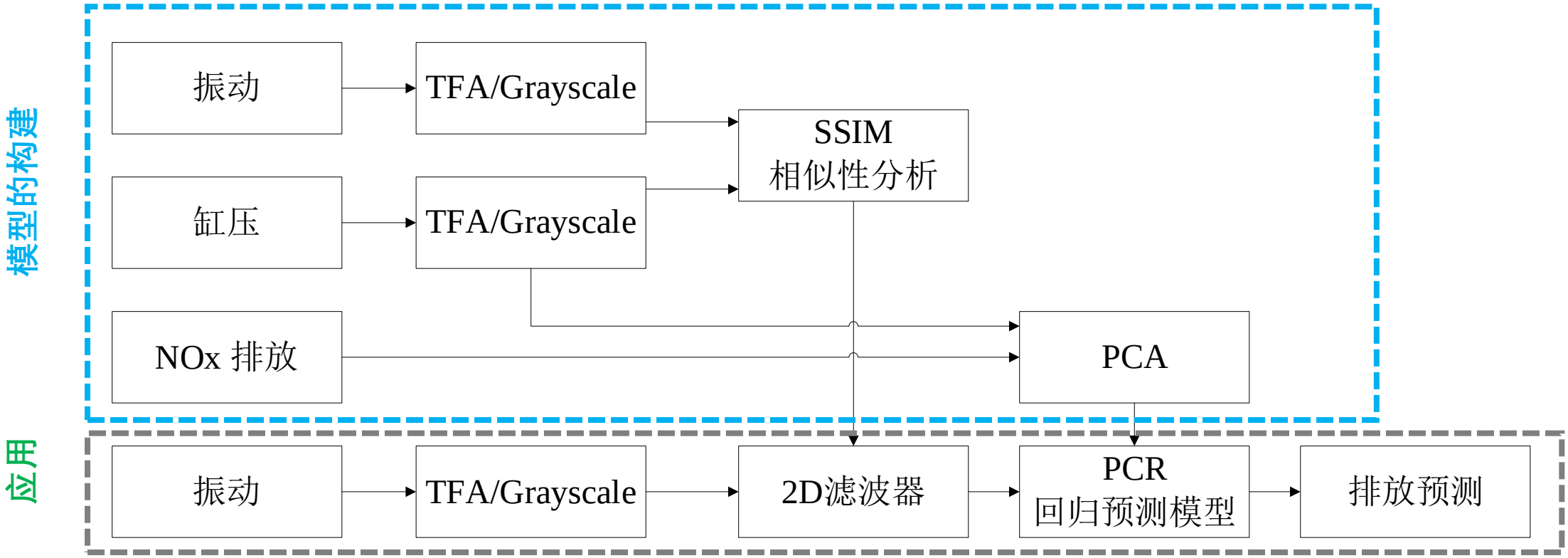
- Combustion shock is one of the most important excitation sources of engine vibration and noise emissions.
- 燃烧冲击是发动机振动和噪声排放的最重要激励源之一。
- The combustion pressure is closely related to the in-cylinder temperature. It has been confirmed that there is a correspondence between combustion pressure and temperature-dependent emissions.
- 燃烧压力与缸内温度密切相关。燃烧压力与排放（与温度相关的NOx/PM）之间存在对应关系。

排放与振动的关联 Correspondence between emissions and vibration



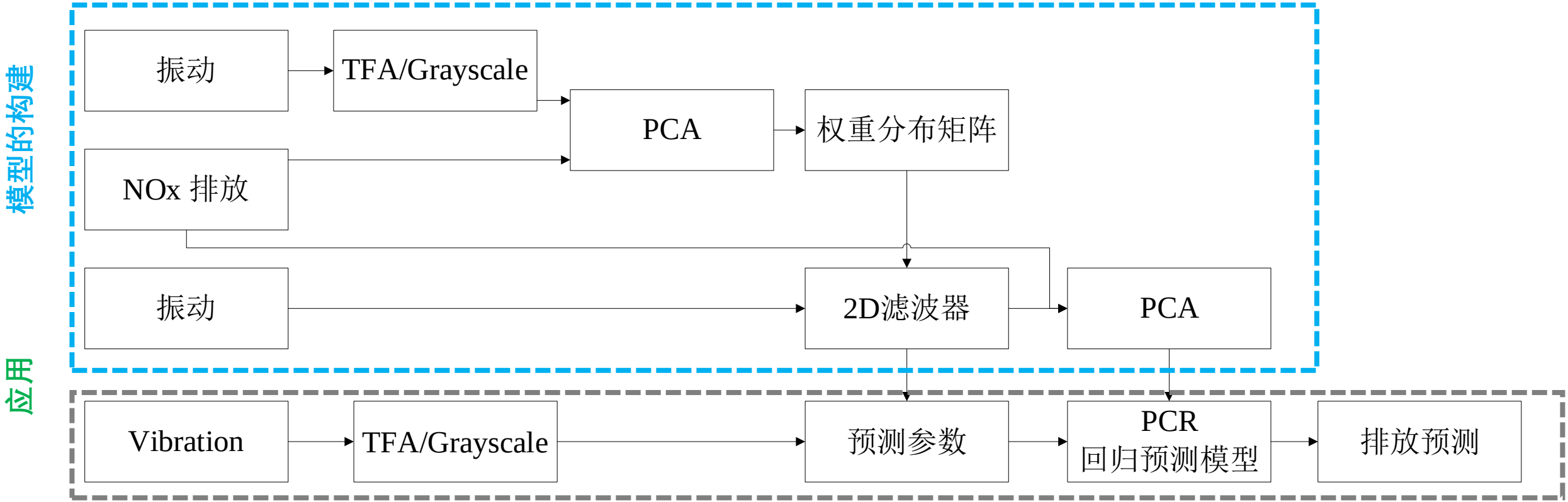
Vibration Based Virtual Sensing of NOx Emission in CI Engines
基于振动信号的柴油机NOx排放虚拟传感研究

技术路线1 Technical route 1



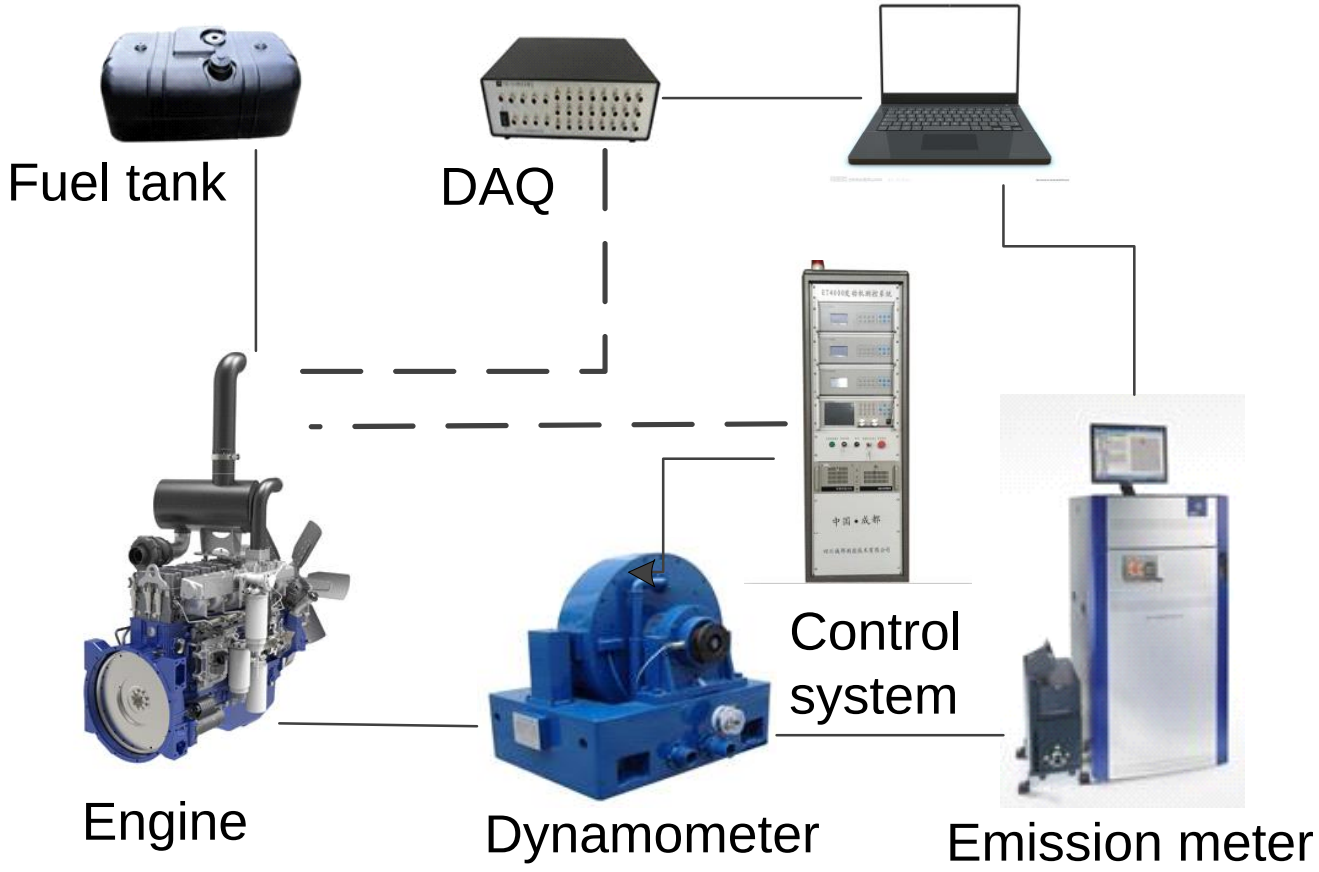
- Combustion behavior is the link between vibration and emissions. Therefore, the first technical route is centered on cylinder pressure reconstruction.
- 燃烧行为是振动与排放联系的关键。 因此，第一个技术路线的重点是缸内压力的重构。
- Designing a filter based on the similarity between in-cylinder pressure and vibration makes the extraction of predictive variables from vibration signals more efficient.
- 根据缸内压力和振动之间的相似性设计滤波器，可以更有效地从振动信号中提取预测变量。

技术路线2 Technical route 2



- Since the relationship between vibration and emissions is definite, we can directly analyze the correlation between the two and build a more concise predictive model.
- 由于振动和排放之间的关系是确定的，因此我们可以直接分析两者之间的相关性，并建立更简洁的预测模型。

Design of experiments



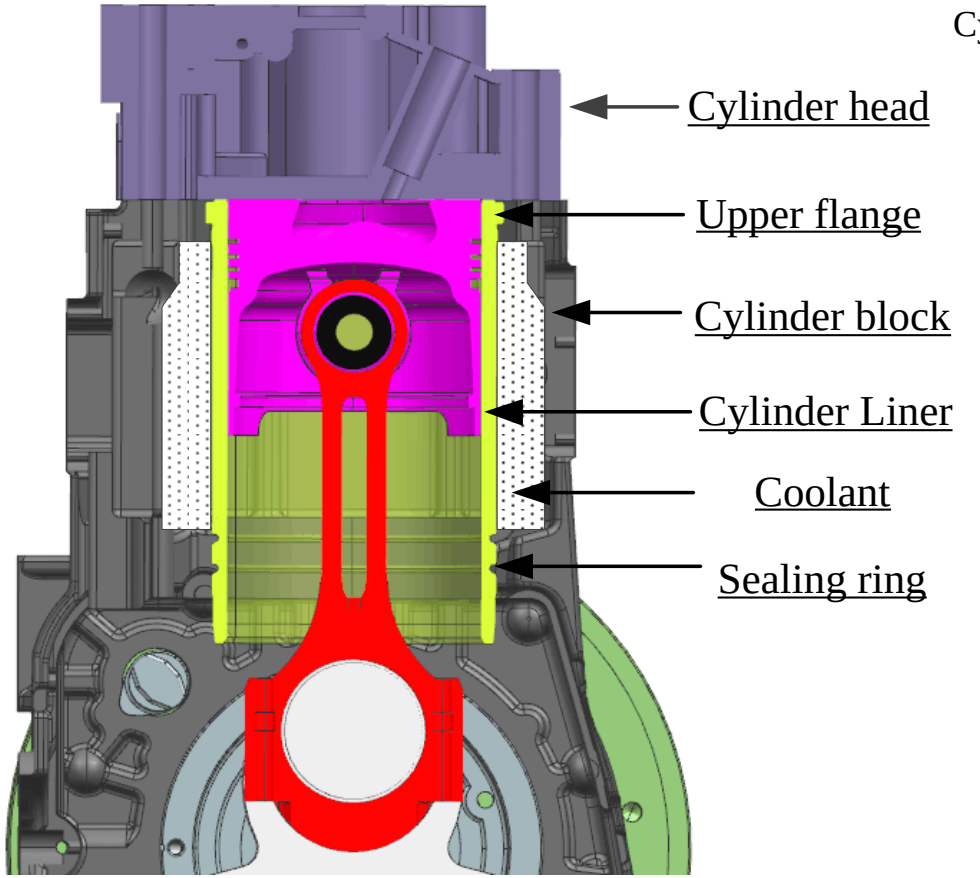
台架参数
Specification of the test engine

Manufacturer	Quan Jiao Power Co., Ltd., PR. China
Engine model	QCH1110
Number of cylinders	single
Bore/stroke /mm	125/120
Compression ratio	18
Rated power/ kW	14.7

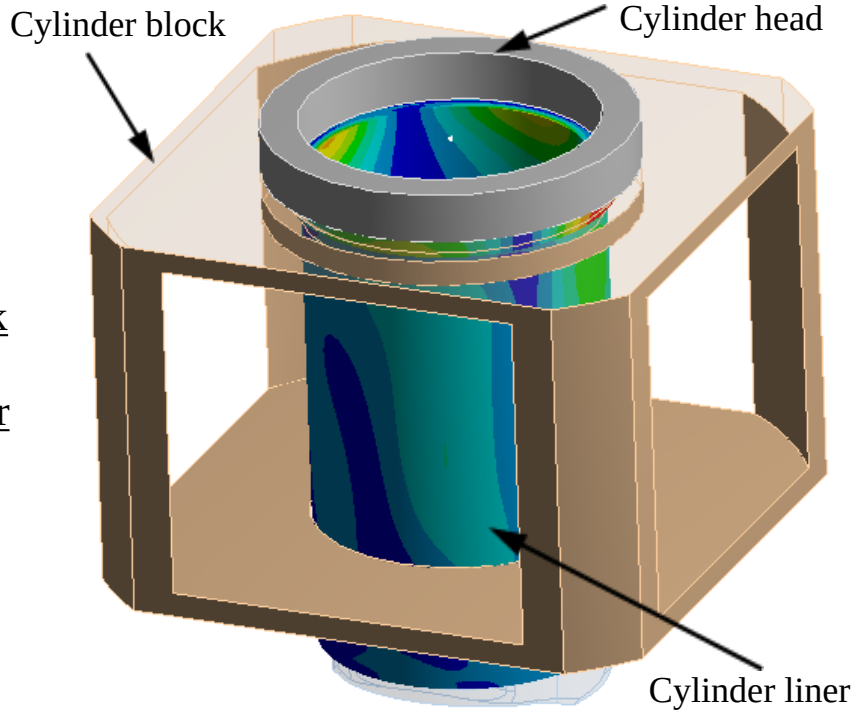
转速 speed：1200r/min、1400r/min、1600r/min、1800r/min
负荷　load：10N.m、30N.m、50N.m

燃烧与振动的关联 Correspondence between combustion and vibration

模型1：FEM-based dynamic model

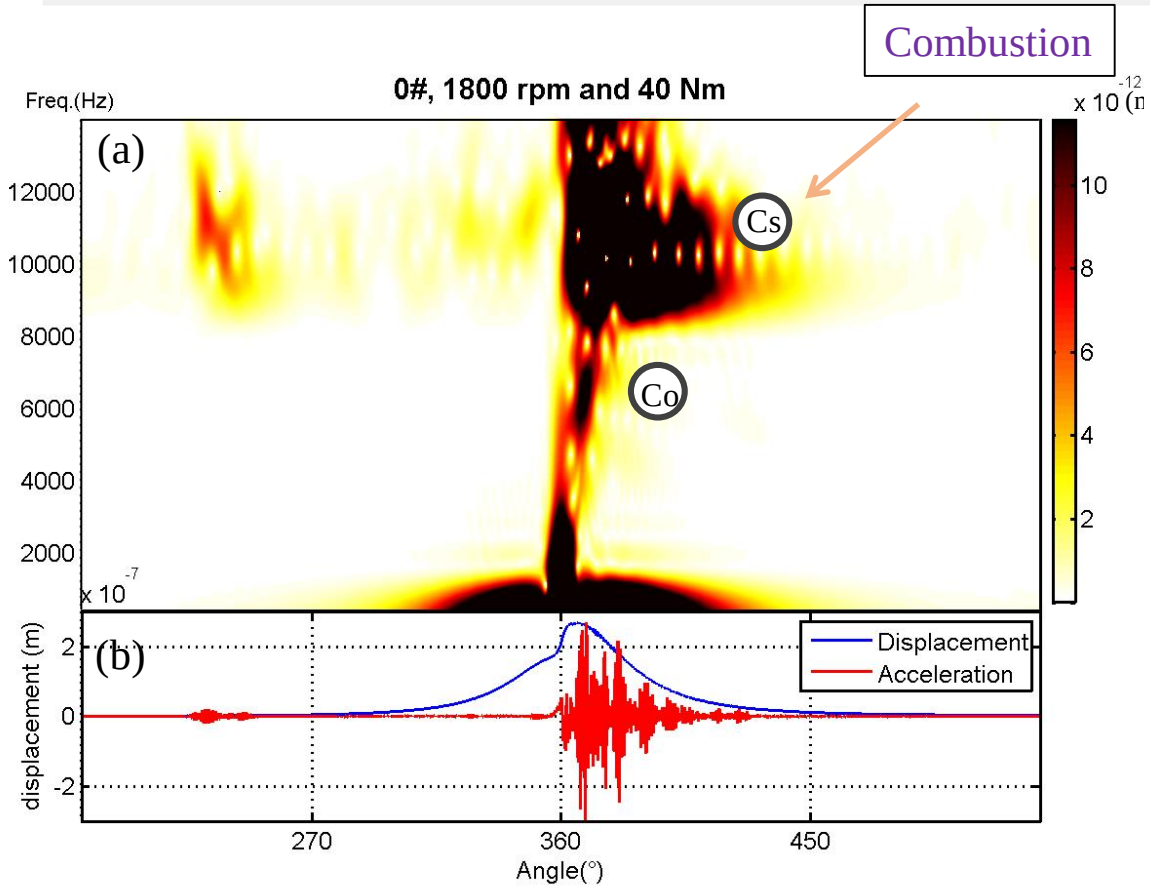


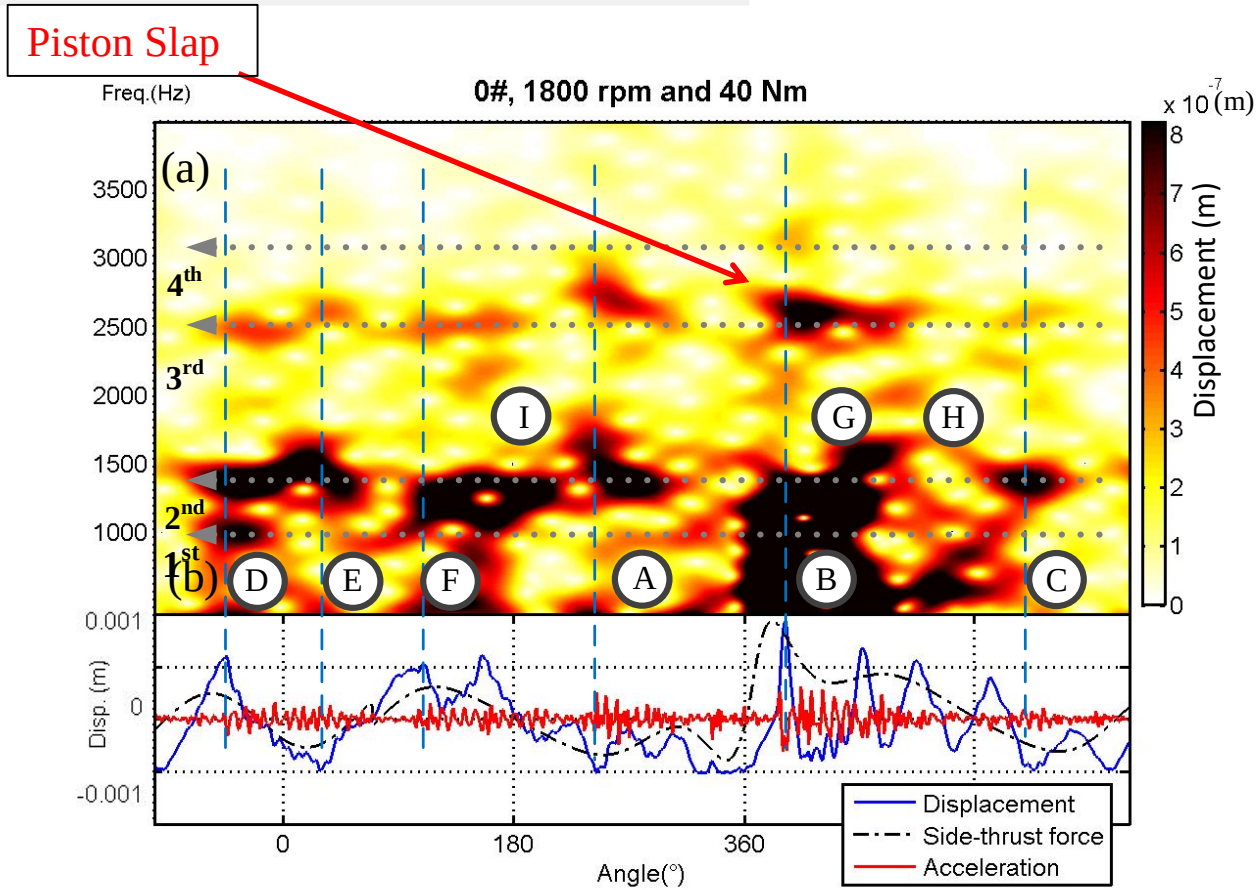
Establishment of Finite Element Model



- (结构模态 **Modal characteristics**)
  Structural transient dynamics simulation
- (非线性约束 **Contact constraints**)
  Nonlinearities of assembly constraint

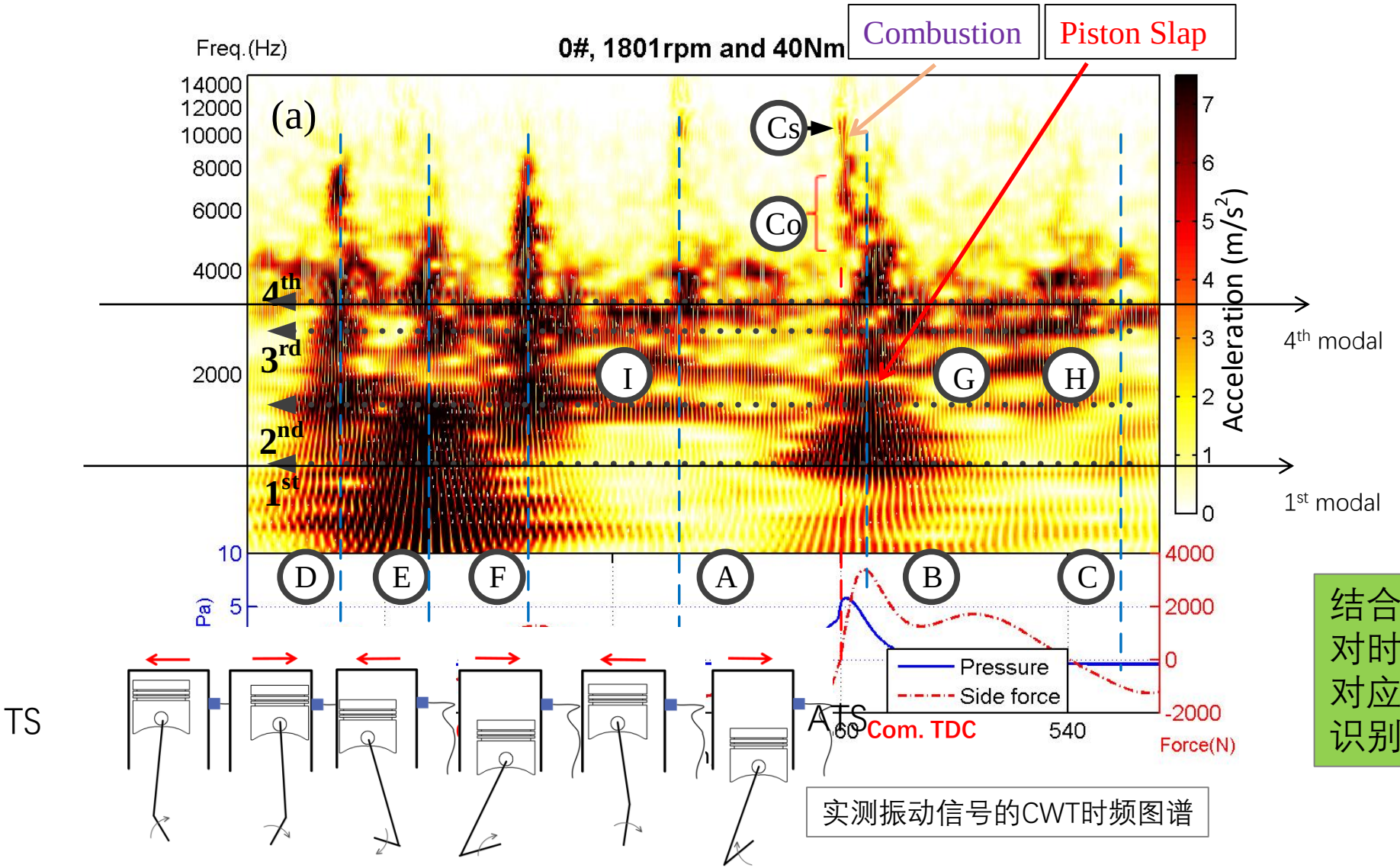
燃烧与振动的关联 Correspondence between combustion and vibration





分别仿真了燃烧冲击与活塞侧击引起的缸套振动响应

燃烧与振动的关联 Correspondence between combustion and vibration

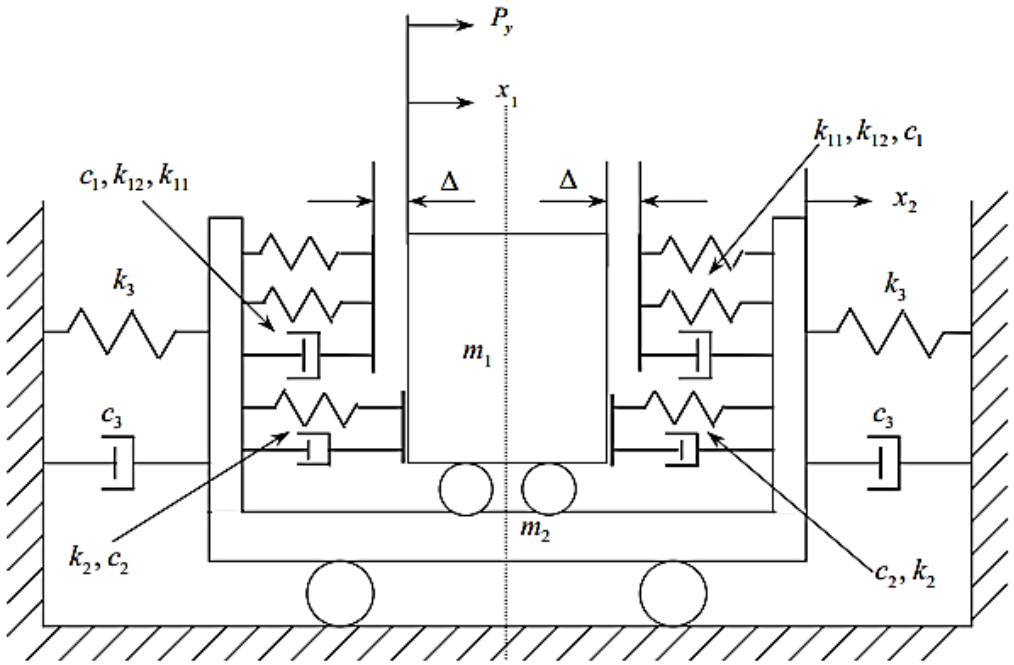


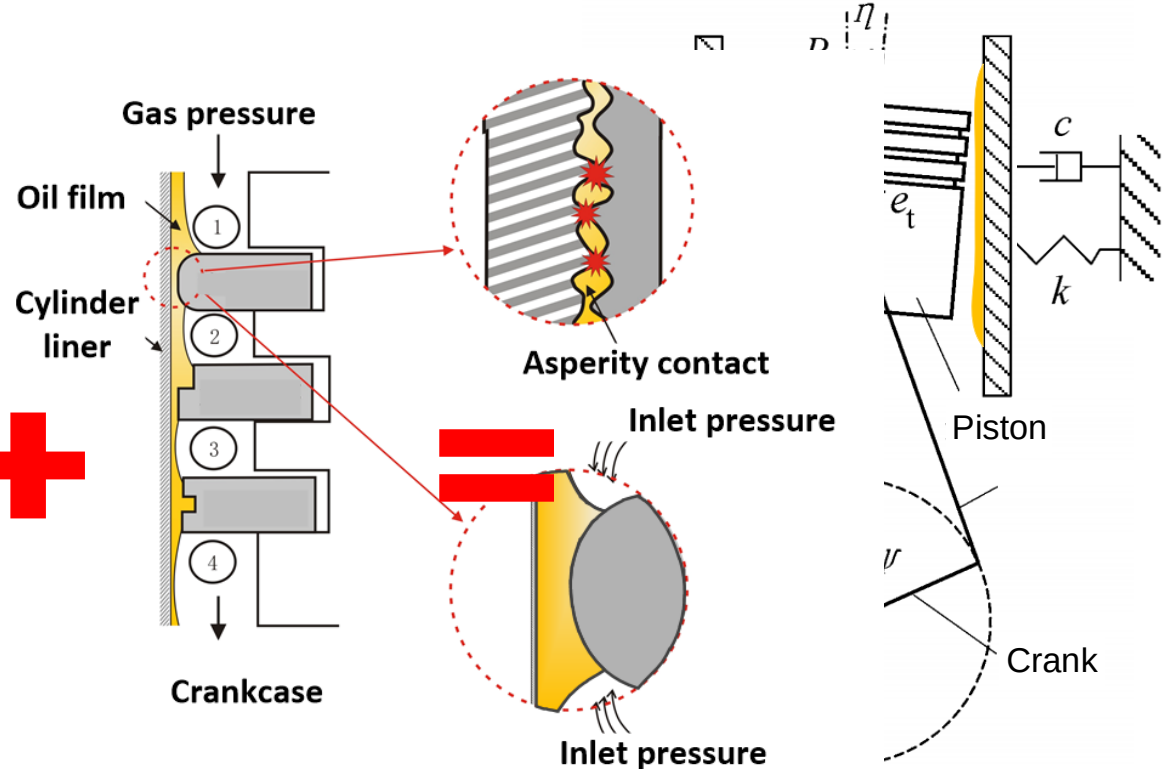
实测振动信号的CWT时频图谱

结合仿真与实测振动分析，对时频域上不同振动响应对应的激励源事件进行了识别与解耦。

燃烧与振动的关联 Correspondence between combustion and vibration

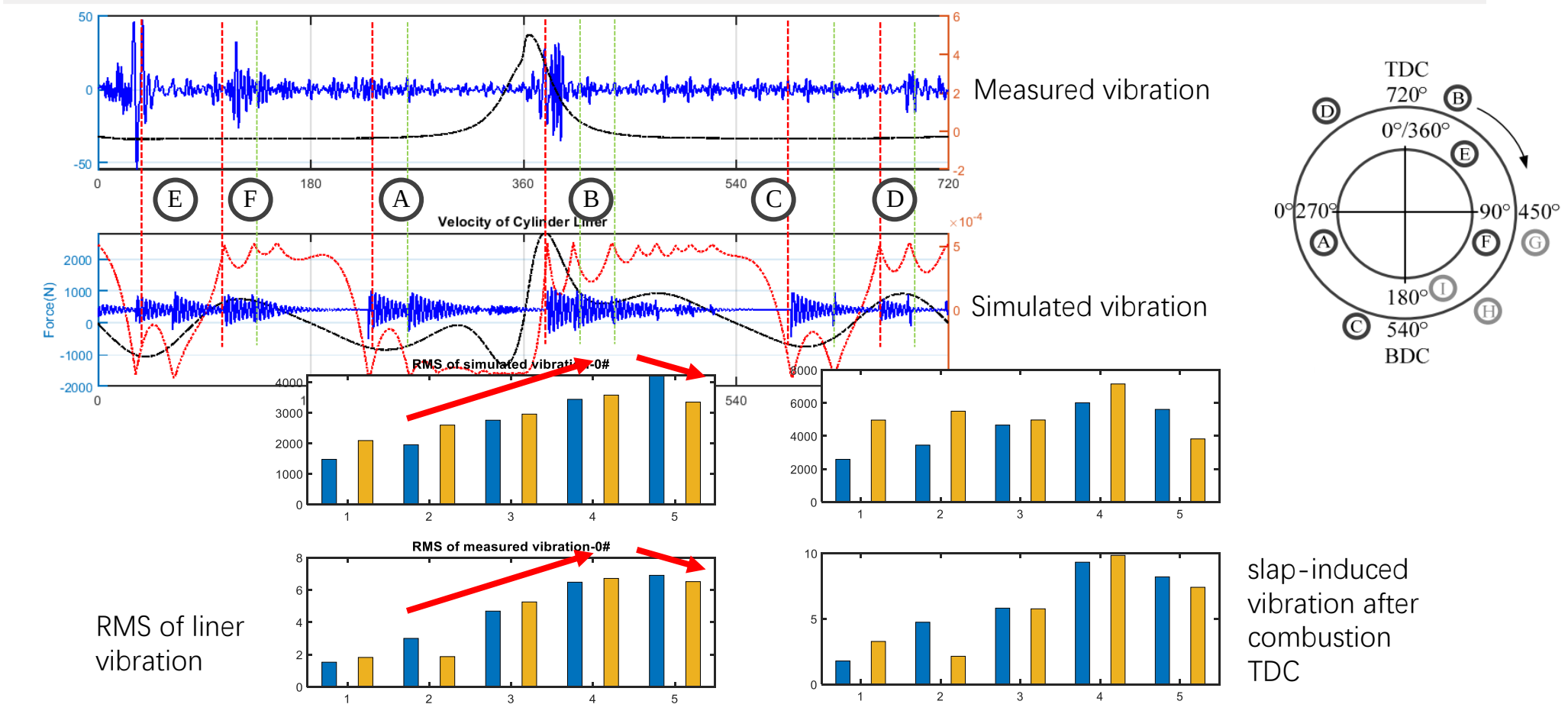
模型2： Combination of dynamic and tribological model





结合结构动力学与弹流动力学模型构建了一种活塞-缸套组件的非线性动力学模型，对燃烧特性、结构动力学和油膜动力学特性耦合造成的缸套动力学响应进行了数值预测。

燃烧与振动的关联 Correspondence between combustion and vibration

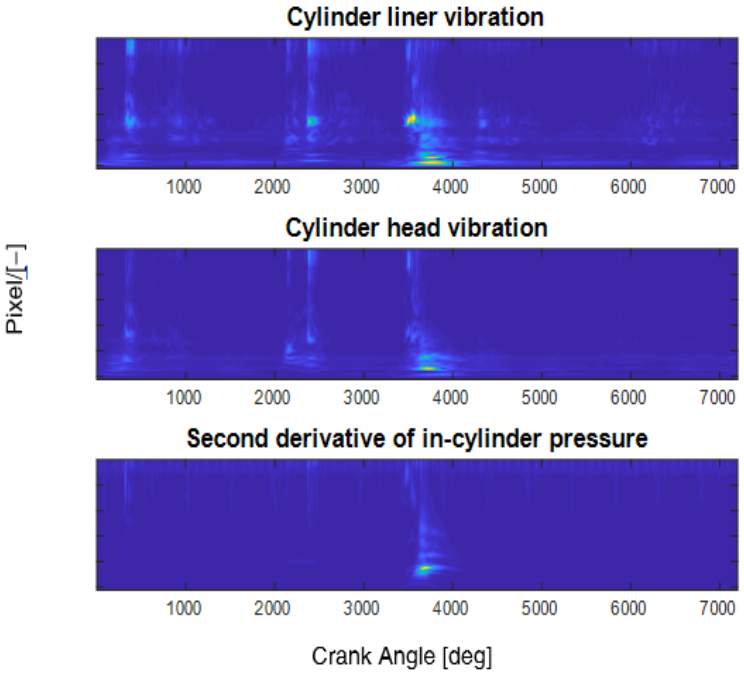


摩擦动力学模型可以有效预测缸套随转速升高产生的非线性变化趋势。

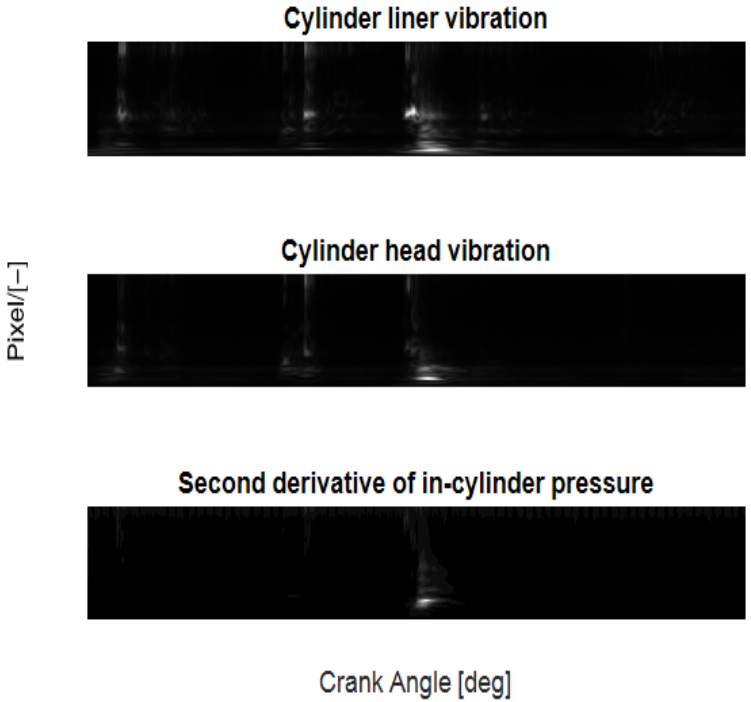
The tribo-dynamics model can effectively predict the non-linear trend of vibration response with increasing speed.

缸压重构 Reconstruction of in-cylinder pressure

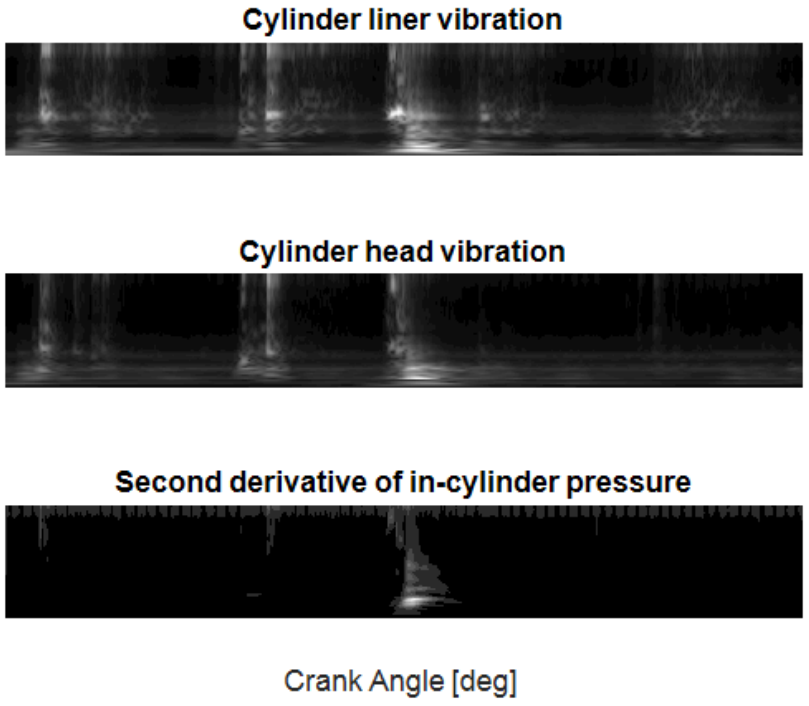
1. 时频图谱的灰度化 Image graying



(a) Selection of source data



(b) Grayscale images of time-frequency spectra



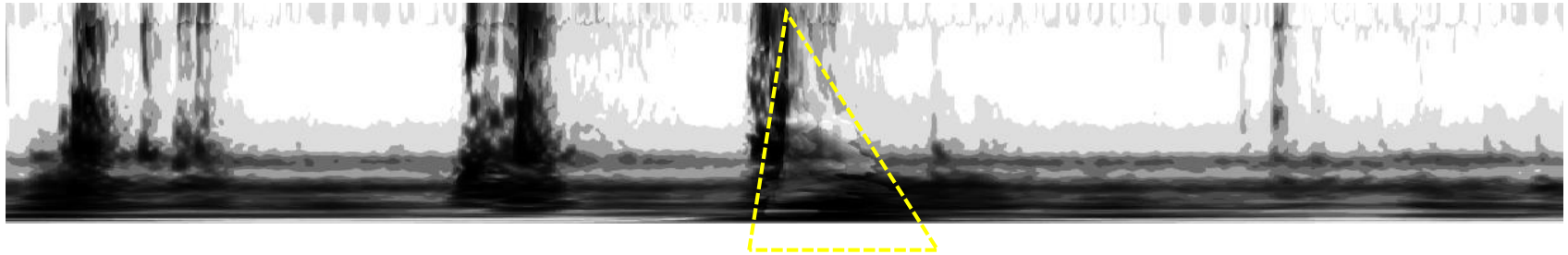
(c) Grayscale images after gamma correction

- To facilitate the normalized similarity analysis of vibration and pressure, it is necessary to first gray-scale the time-frequency matrices of measured signals.
- 为便于对振动和压力进行归一化相似性分析，必须首先对测量信号的时频矩阵进行灰度处理。
- In order to highlight more detailed information, a gamma correction process is performed on linear RGB images.
- 为了突出显示更多详细信息，对线性RGB图像进行了伽玛校正。

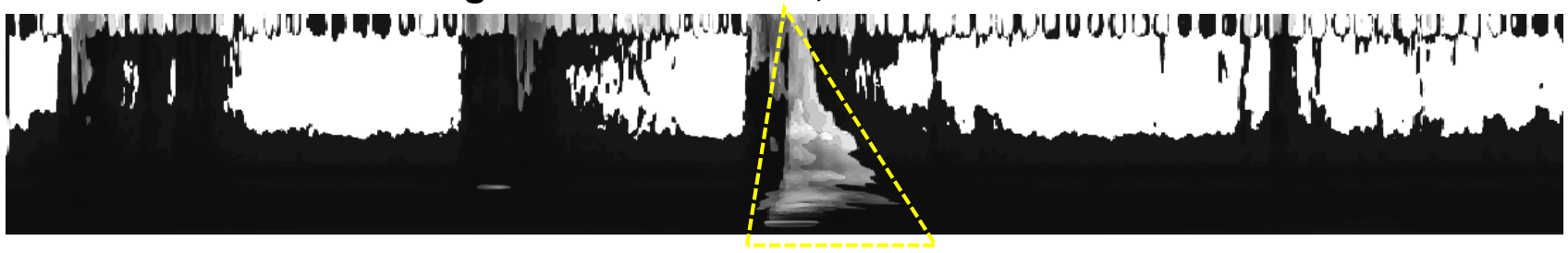
缸压重构 Reconstruction of in-cylinder pressure

2. 结构相似性分析 SSIM analysis

Before gamma correction, Mean SSIM= 0.6571



After gamma correction, Mean SSIM= 0.3598

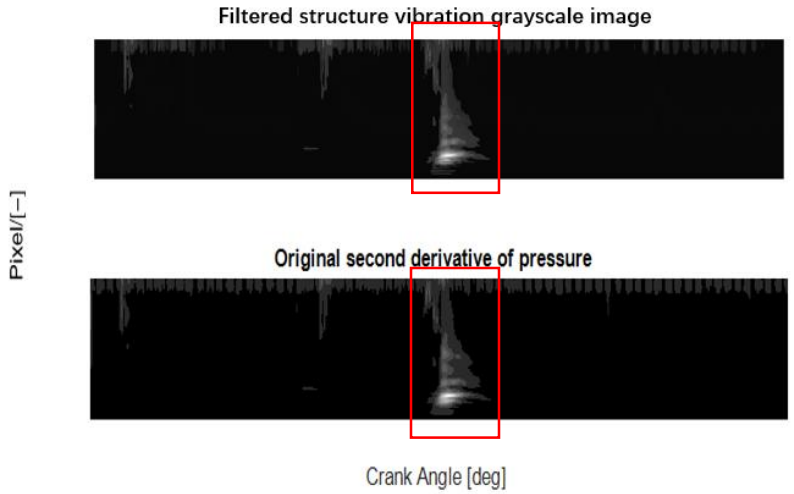


SSIM maps of pressure and vibrations before and after gamma correction

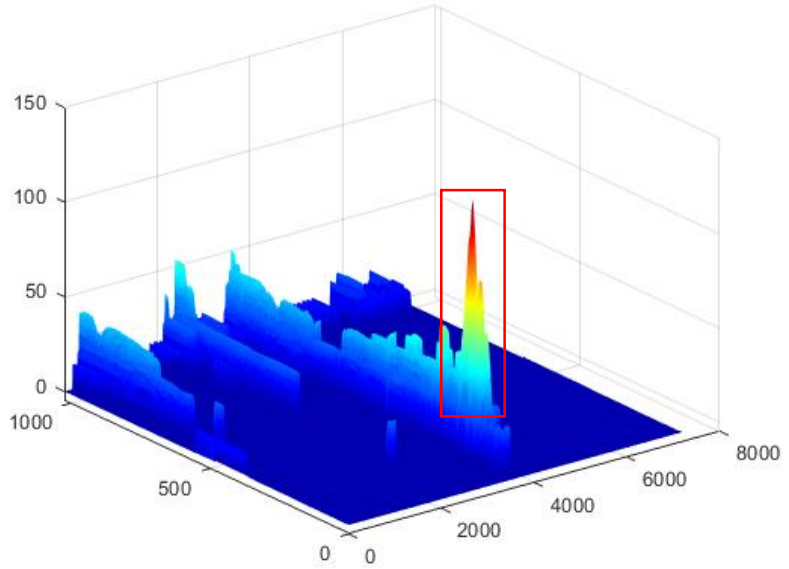
- SSIM map of in-cylinder pressure and head vibration after gamma correction shows more obvious similarity pattern related to combustion event, as marked by the triangle frame.
- 缸内压力和经过伽马校正后的缸盖振动的SSIM图显示了与燃烧事件相关的更明显的相似性模式，如三角框所示。
- Based on the similarity map, a two-dimensional filter can be designed.
- 基于相似度图，可以设计用于缸压信号重构的二维滤波器。

缸压重构 Reconstruction of in-cylinder pressure

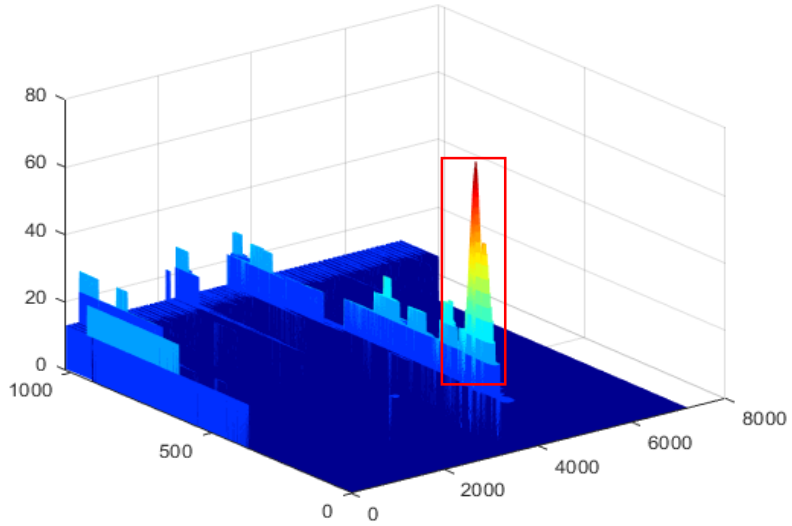
3. 缸压重构 Pressure reconstruction



（a）Filtered grayscale image and original second-order derivative of pressure



（b）Time-frequency representation of filtered structural vibration

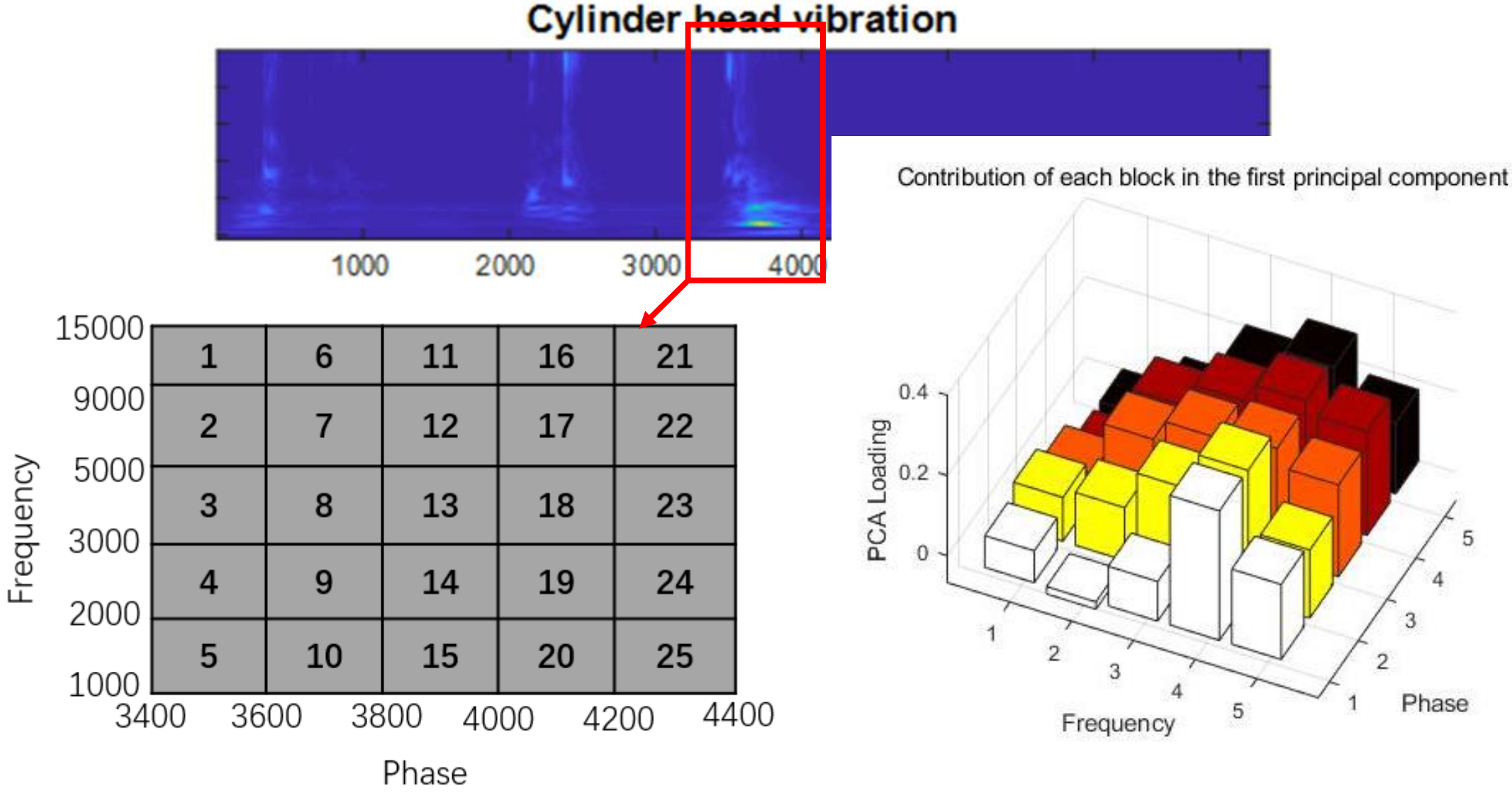


（c）Time-frequency representation of original second-order derivative of pressure

- Reconstructed second-order pressure accurately retains fluctuation information related to combustion shocks.
- 重建的缸压二阶导信号可准确再现与燃烧冲击有关的波动信息。
- Based on the reconstructed cylinder pressure, predictive variables can be selected for establishment of a predictive model.
- 基于重构的缸内压力，可以选择预测变量以建立预测模型。

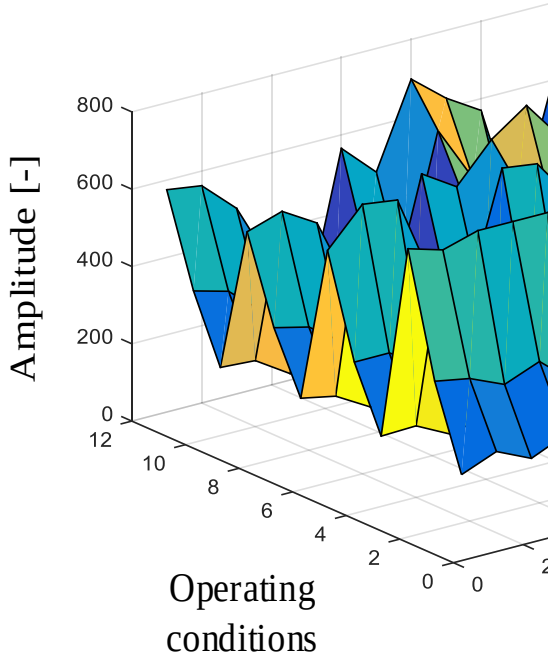
权重分布分析 Weight distribution of vibration events

技术路线2 Technical route 2

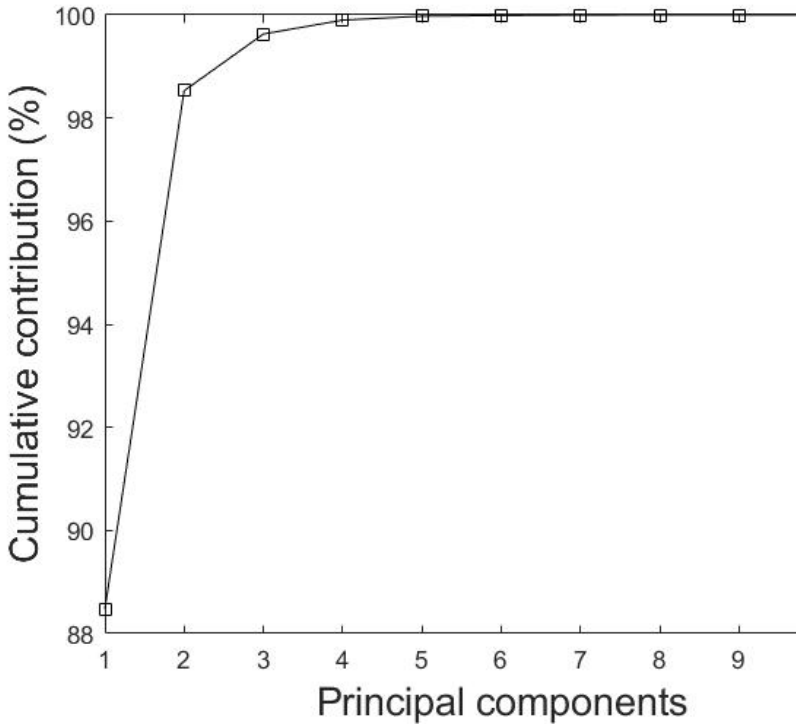


排放虚拟监测 Virtual sensing of NOx emissions

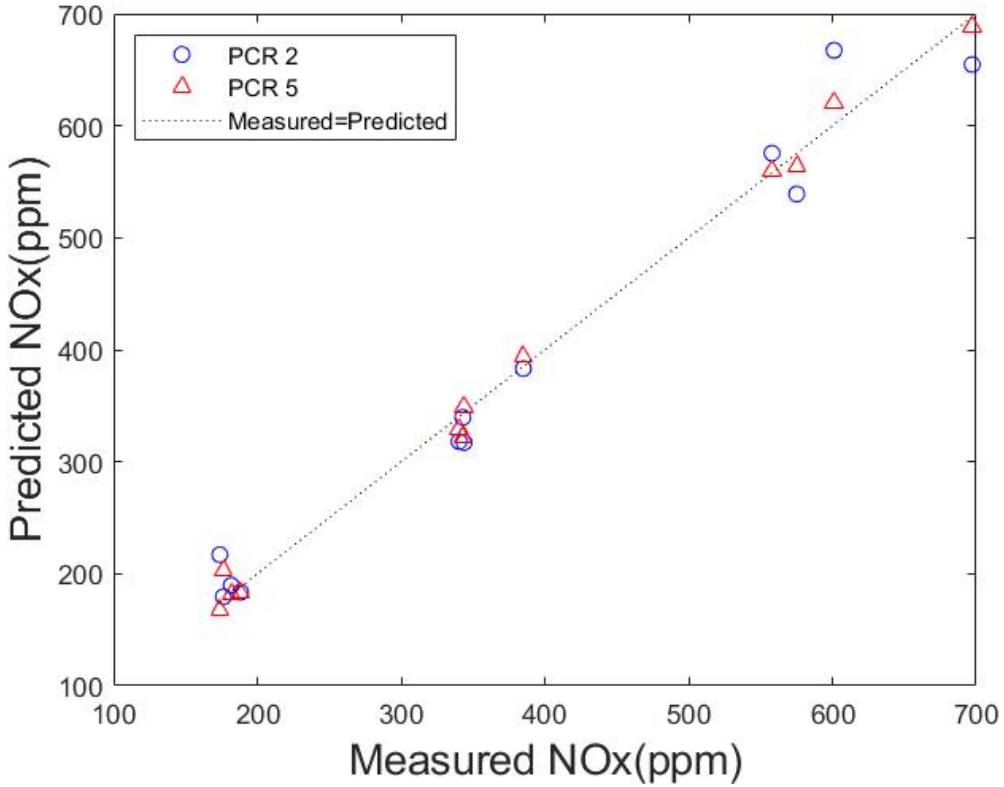
a. Predictor variables



b. Principal component analysis



c. Comparison of predicted and measured NOx



There is a good correlation between structural vibration characteristics and measured NOx emissions.

结构振动特性与测得的NOx排放之间存在良好的相关性。

This provides a novel way for low-cost transient emission monitoring.

这为低成本的瞬态排放监测提供了一种新颖的方法。

Conclusions

- By comparing the measured NOx emissions with the predicted values, it can be known that the regression model constructed based on the reconstructed cylinder pressure from vibration signals has a good prediction of diesel engine NOx emissions under various operating conditions. The coefficient of determination (R2) between the predicted value and the measured value is 0.971~0.995.
- 通过对NOx排放量实际测量值与预测值进行比较，可以知道，基于振动信号重构的缸内压力构建的回归模型可以很好地预测多种工况下的柴油机NOx排放量。 预测值和测量值之间的确定系数（R^2）达到了0.971～0.995。
- The vibration-based virtual sensor of NOx emission (or PM emissions) is expected to provide a cost-effective non-intrusive on-line monitoring technology for vehicles in real-driving emissions.
- 基于振动的NOx排放（或PM排放）虚拟传感器有望为实际行驶中的车辆提供经济高效的非侵入式在线监测技术。

THANK YOU

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