# 内燃机状态监测用振动信号预处理技术及特征参数提取方法研究

2020

Research on vibration signal preprocessing and extraction method of combustion parameter

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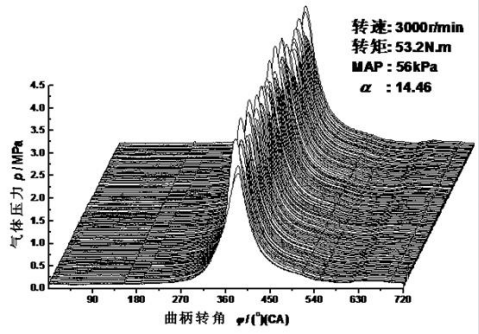
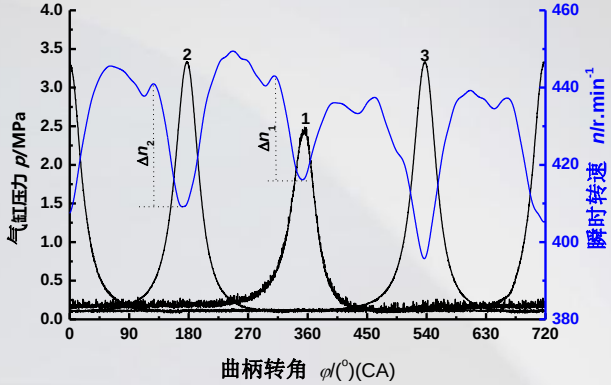
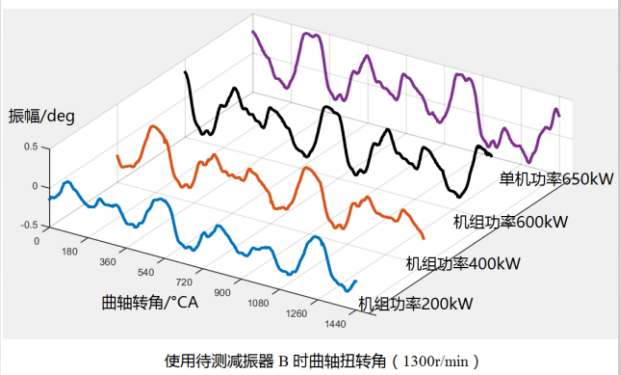
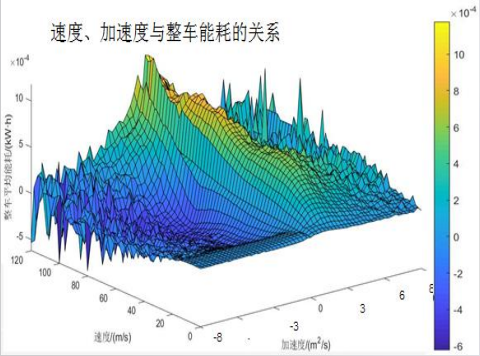
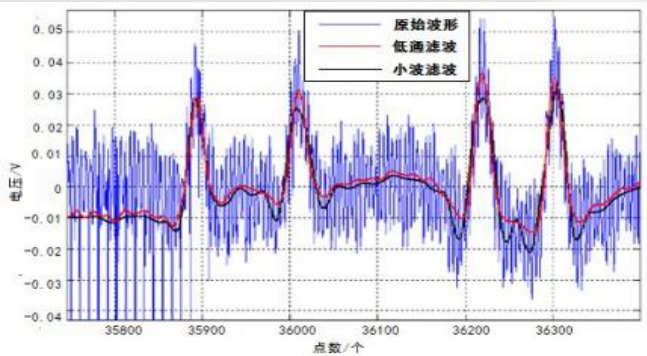
1. 课题组主要从事信号测试分析及控制技术方面的研究工作；
2. 近年来承担国家973课题，国家重点研发计划、国家863计划，国家自然科学基金，山东省重大科技创新工程，山东省自然科学基金及山东省重点研发计划2项，其他省部级课题20余项，企业委托课题50余项；
3. 发表学术论文100余篇，其中，SCI/EI收录50余篇；
4. 申请专利30余项；
5. 申请软件著作权40余项。

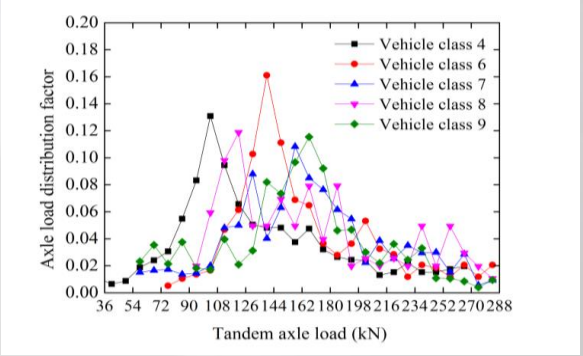



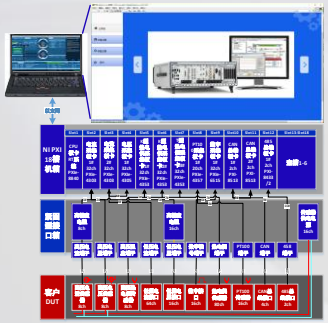



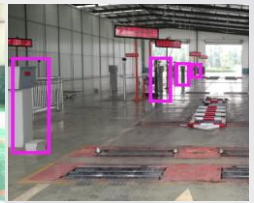




**课题组针对缸压、瞬时转速、扭振、新能源车辆运行数据及交通数据等不同类型数据的测试及分析方法展开研究工作。**

在康明斯ISG发动机部件性能测试中得到应用



在潍柴燃料电池车辆性能测试中应用

汽车检测线测控系统，累计销量万余套

在G3、G30、G110、G204、G206等全国近20条道路得到推广

**课题组开发的多款设备在动力装置（内燃机、燃料电池）、车辆及智慧交通等领域得到推广应用。**

1. 研究背景

Research background

2. 燃烧激励及其响应信号相关性分析

Correlation analysis between combustion and vibration

3. 振动信号测试方法及分析方法

Measured and analysis method of vibration signal

4. 基于振动信号的燃烧特征参数提取

Combustion parameter extraction from vibration signal

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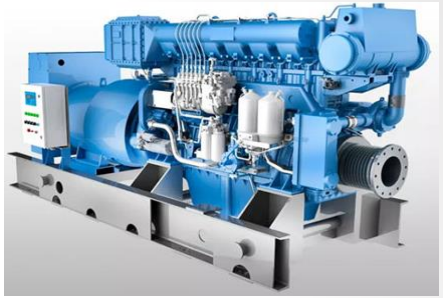
# 1. 研究背景/Research background








- 内燃机具有热效率高、扭矩大及功率范围广等优点

Internal combustion engine （ICE）has the advantage of high thermal efficiency, high torque and wide power range.

- 在车用动力、船舶动力及非道路动力机械等领域得到了大量的推广应用

ICE has been widely used in vehicle, ship and non-road power.

# 1. 研究背景/Research background

- 对内燃机缸内燃烧状况进行监测和控制，保持其良好的使用状态， 这对于内燃机的节能减排都有重要的实用意义

ICE can be kept in good condition by monitoring and controlling the combustion process, which can be contributed to energy conservation and pollution reduction.

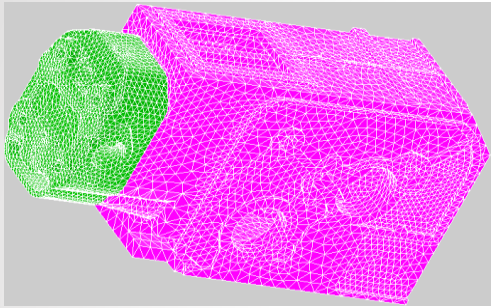
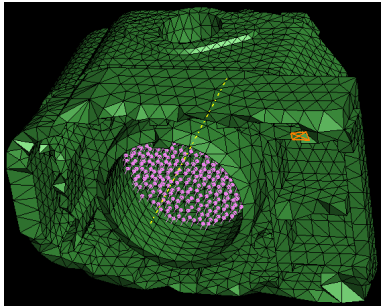
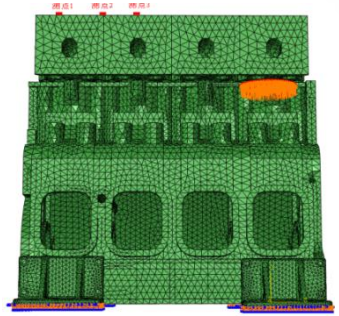
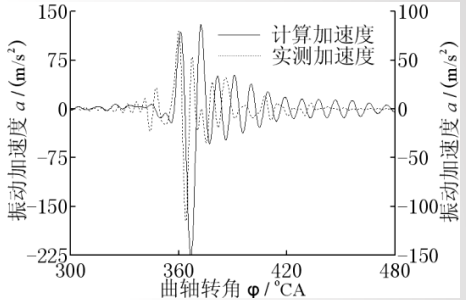
- 内燃机表面振动信号包含丰富的柴油机工作状态信息；振动传感器成本低，安装方便，满足长期监测的要求；利用振动信号估计内燃机缸内燃烧状况具有重要的研究价值。

Vibration signal contains abundant useful information of combustion process.

Vibration signal has the advantage of low cost and easy installation, which was suitable for long-term monitoring.

Estimation of combustion process with vibration signal has important research value.

# 2. 燃烧激励及响应相关性分析/Correlation analysis between combustion and vibration


- 利用振动信号评价缸内燃烧状况时，需要了解燃烧激励与其响应信号之间的关系；

Before the estimation of combustion process with vibration, it is necessary to understand the relationship between the two signals.

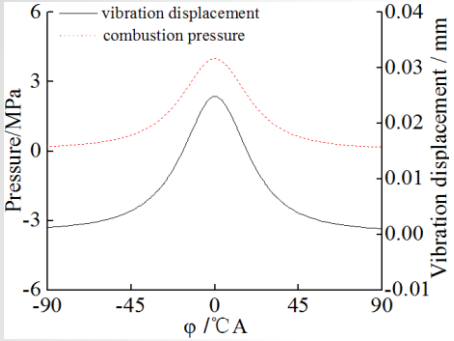
- 柴油机运行过程中，缸盖、机体及联接螺栓组成了弹性系统，在此，基于有限元方法建立了内燃机分析模型；

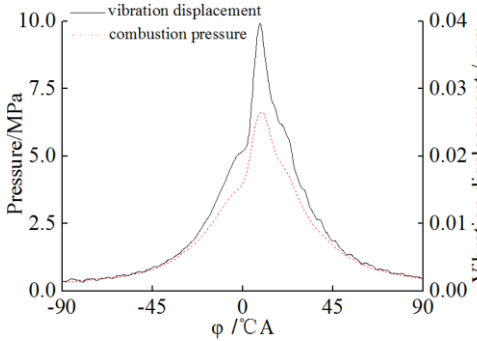
The FEA method was used to establish model for single and four cylinder engine.

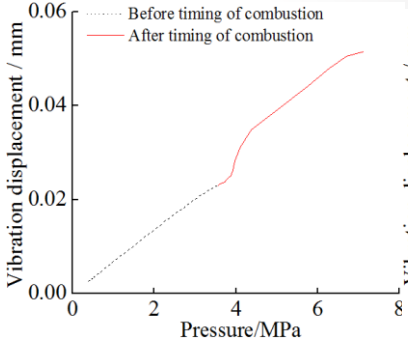
- 以实测缸压作为激励，计算只有缸压激励情况下，缸盖表面振动响应信号；对燃烧激励及其响应信号之间的关系进行分析。

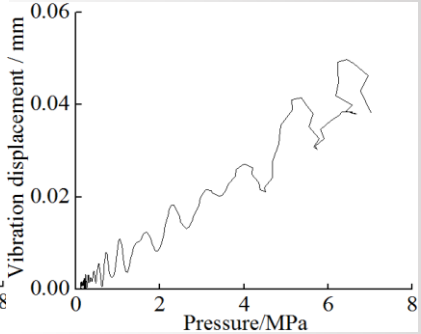
Measured pressure is exerted on the model and vibration signal is calculated to study the correlation between the two signals.

# 2. 燃烧激励及响应相关性分析/Correlation analysis between combustion and vibration




- 反拖工况，计算位移与缸内压缩压力呈良好的对应关系；

**The trend of combustion pressure and vibration displacement was similar when engine was driven by motor.**

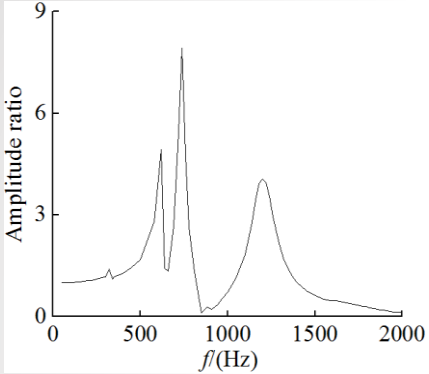
- 正常燃烧工况，缸内燃烧压力与缸盖位移呈显著的分段特性：峰值压力以前，位移的变化趋势与缸内燃烧压力的变化趋势基本相同；峰值压力后，位移波形呈现振荡的趋势。

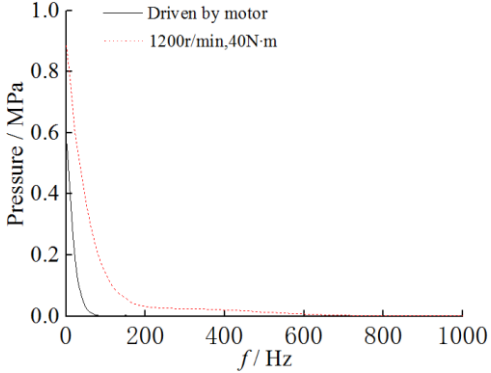
**When the engine was operated normally, the relationship between the two signals can be divided into two stages by appearance timing of peak pressure.**

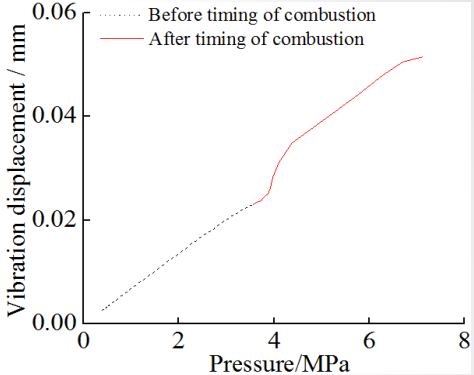
**The trend between the two signals was similar before the appearance timing of peak pressure, especially before the start timing of combustion.**

**The vibration displacement fluctuated obviously after the appearance timing of peak pressure.**

# 2. 燃烧激励及响应相关性分析/Correlation analysis between combustion and vibration




- 将内燃机作为测试系统，缸压是输入，振动是输出；计算系统的动态响应特性，与不同工况的缸压频谱进行对比；

The amplitude-frequency characteristic of ICE is calculated and compared with the frequency analysis.

- 当激励频率低于固有频率时，燃烧压力与振动位移有良好的线性关系。

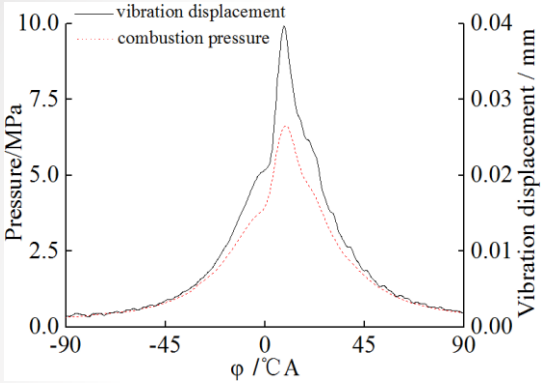
There exists a linear relationship when the excitation frequency was lower than the natural frequency.

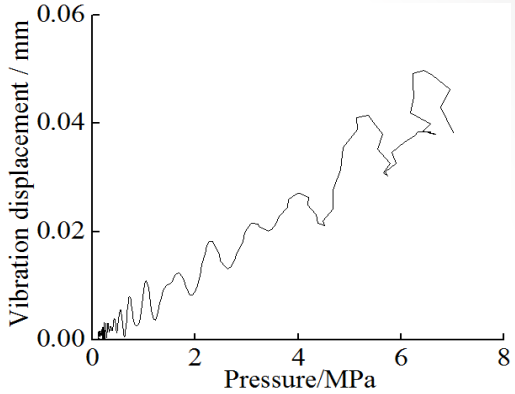
- 燃烧开始后，出现高频成分， 线性关系改变，但在峰值压力出现时刻前，缸压持续增加，振动位移仍呈增大的趋势。

High frequency appears after combustion, the linear relationship changed correspondingly.

Vibration displacement increases with the increase of cylinder pressure before the appearance timing of peak pressure.

# 2. 燃烧激励及响应相关性分析/Correlation analysis between combustion and vibration




- 燃烧峰值压力以后，缸压降低，缸盖振动位移呈振荡的趋势，该时段的振动信号与缸内燃烧过程的相关性减弱；

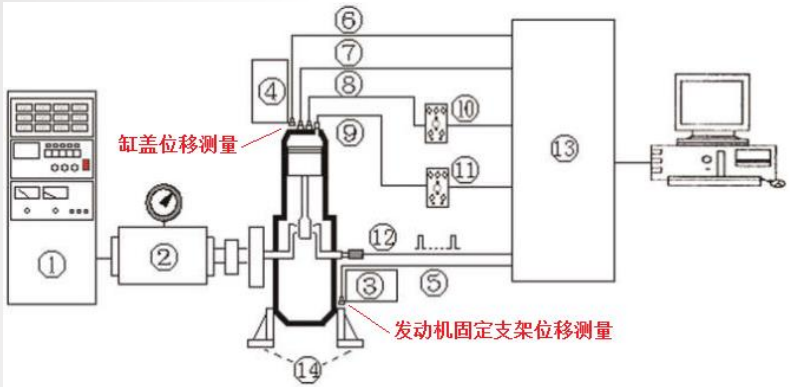
**After the appearance timing of peak pressure, the vibration displacement gradually decreased with fluctuation. The correlation between combustion and vibration weakens.**

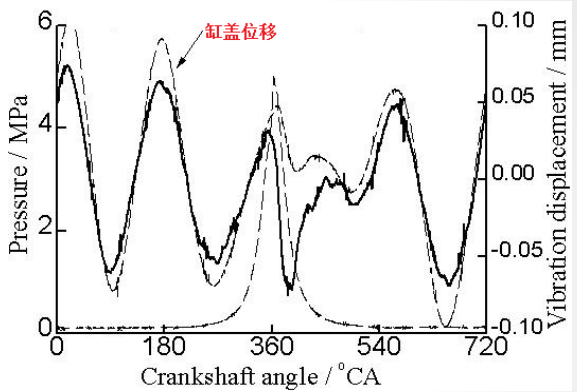
- 燃烧峰值压力出现时刻前的振动信号与缸内燃烧过程密切相关，可以用于提取燃烧相关信息。

**The vibration signal is closely related with combustion process before the appearance timing of peak pressure and can be used to estimate combustion parameters.**

# 3. 振动信号测试方法及分析方法/Measured and analysis method of vibration signal

## 3.1 不同类型传感器测试结果对比：位移传感器 Comparison of sensor type: Displacement sensor




- 固定支架自身具有弹性，在不平衡力作用下，固定支架的振动位移有较大的幅值，且与缸盖振动位移具有相近的变化趋势；

The fixing bracket is elastic and has a certain vibration displacement under the action of unbalanced force.

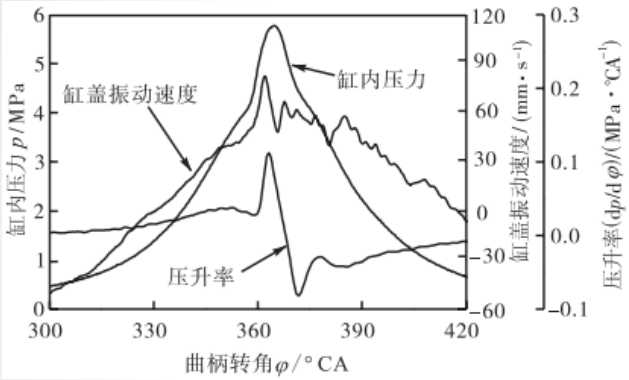
The displacement of fixing bracket has a similar trend with the displacement measured on the cylinder head.

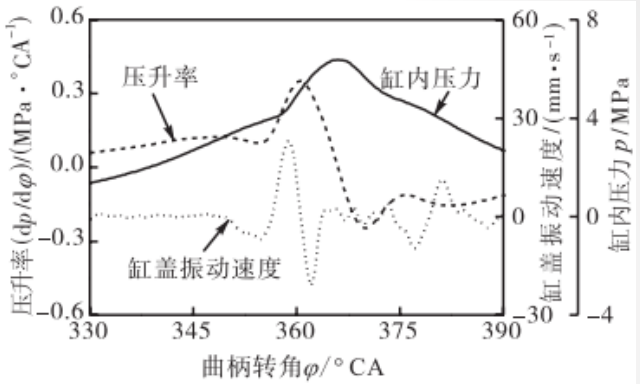
- 缸盖振动位移的主要成分是约束支架的振动位移，燃烧激励产生的振动位移完全被约束支架的振动位移淹没。

The displacement induced by combustion was submerged by the displacement of fixing bracket and hardly to application.

# 3. 振动信号测试方法及分析方法/Measured and analysis method of vibration signal

## 3.1 不同类型传感器测试结果对比：速度传感器 Comparison of sensor type: : Velocity sensor




- 振动速度信号同样受到缸内燃烧激励及固定支架振动的影响，固定支架振动的影响减弱；

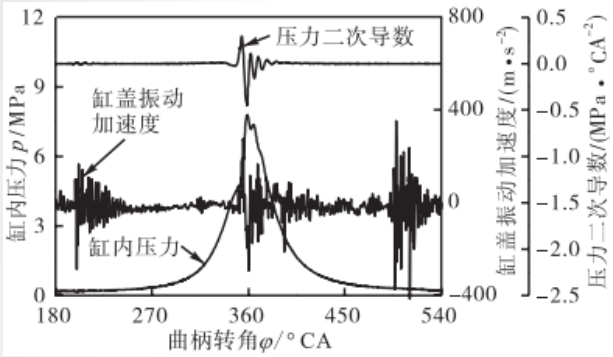
Vibration velocity was also influenced by the fixing bracket, but the degree of the influence is not great.

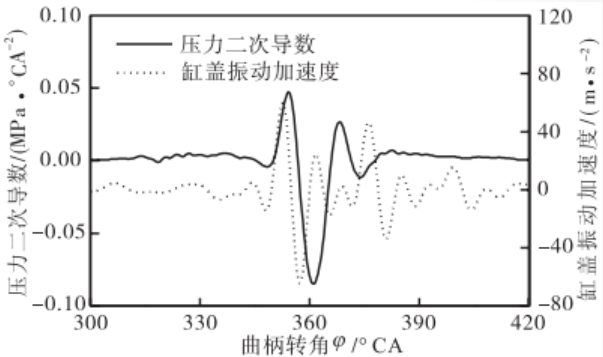
- 处理得到的振动速度信号与压升率的变化趋势相近，而且处理后的振动速度信号与压升率中包含的关键折点，如燃烧起始时刻点、最大压升率位置等出现的时刻接近，蕴含丰富燃烧相关信息。

The treated vibration velocity is closely related with pressure increase rate and contains abundant information about the combustion.

# 3. 振动信号测试方法及分析方法/Measured and analysis method of vibration signal

## 3.1 不同类型传感器测试结果对比：加速度传感器 Comparison of sensor type: Accelerometer




- 振动加速度是振动速度的导数，对高频信息敏感，约束支架低频振动对加速度信号的影响会进一步削弱；

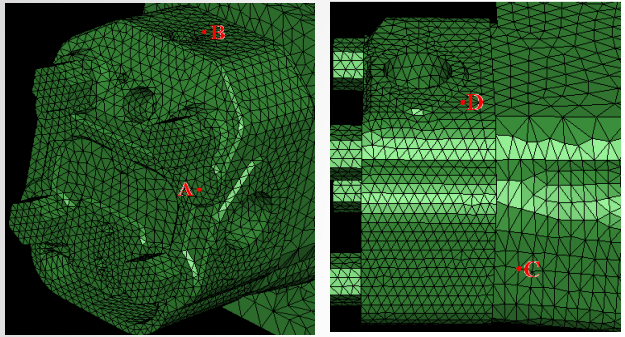
Vibration acceleration is the derivative of velocity and is sensitive to high frequency component.

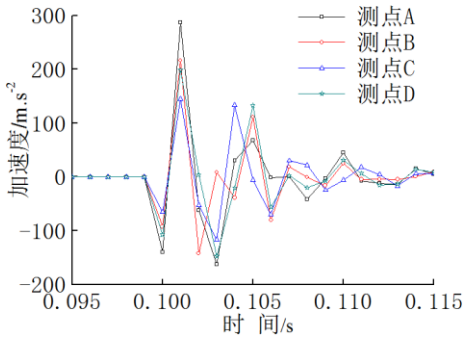
- 低通滤波处理后的缸盖振动加速度及缸内压力二次导数的对比，在燃烧主要阶段的变化趋势相近，振动加速度信号中包含较多燃烧相关的信息，可以用于提取缸内燃烧特征参数。

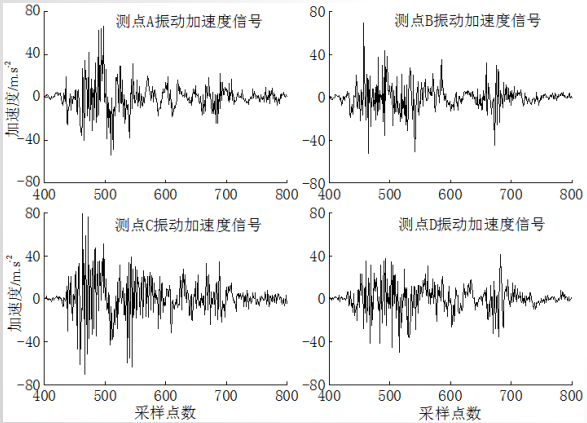
Vibration acceleration is closely related with the second derivative of combustion pressure and can be used to extract the combustion information.

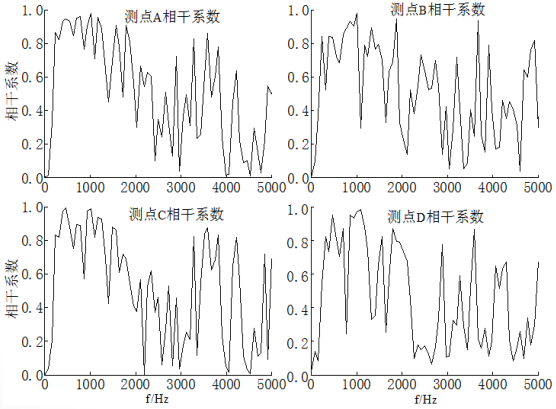
# 3. 振动信号测试方法及分析方法/Measured and analysis method of vibration signal

## 3.2 传感器安装位置/ Confirmation of sensor location




- 通过有限元模型，施加模拟的激励，并比较不同位置在该激励下响应的幅值，来得到敏感测点

FEM model can be used to confirm the optimum sensor location.

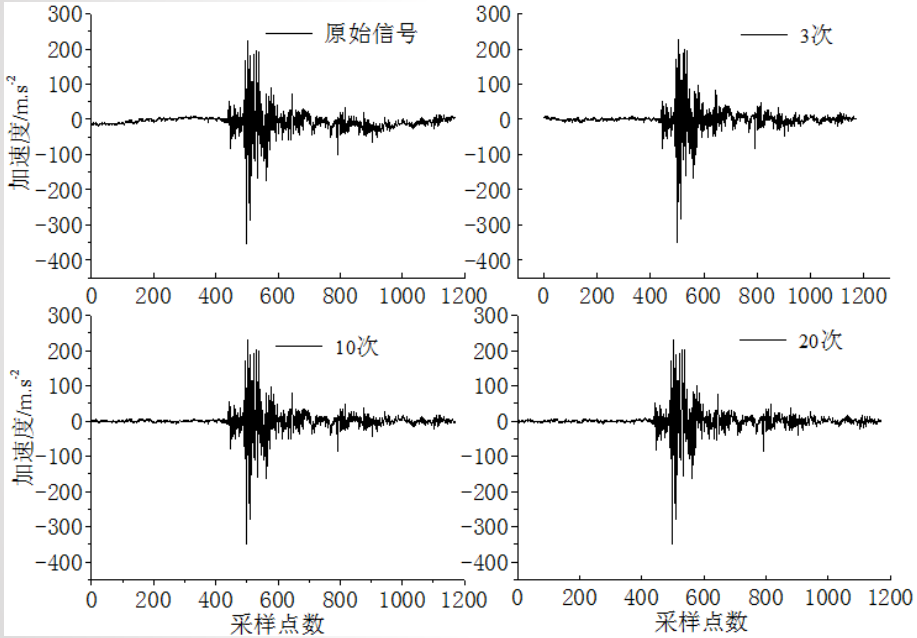
- 实测各测点的加速度，通过缸压与振动加速度的相干系数验证有限元分析的有效性

Coherence coefficient is calculate to verify the analysis of FEA.

- 沿着气缸轴线方向布置加速度传感器更为合理

Vibration sensor should installed in the axis direction of the cylinder.

## 3.3 振动信号预处理方法对比/ Comparison of digital filtering method



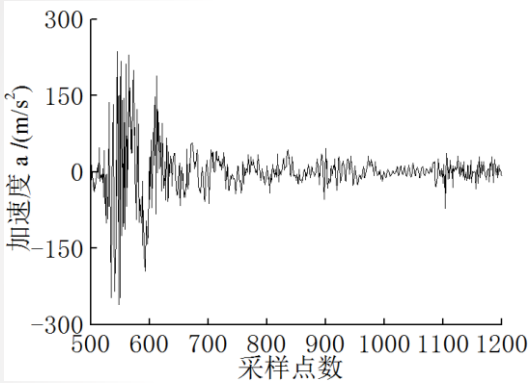

- 测试设备本身性能或外界因素导致测试的振动信号存在零点漂移或长周期趋势项等干扰；

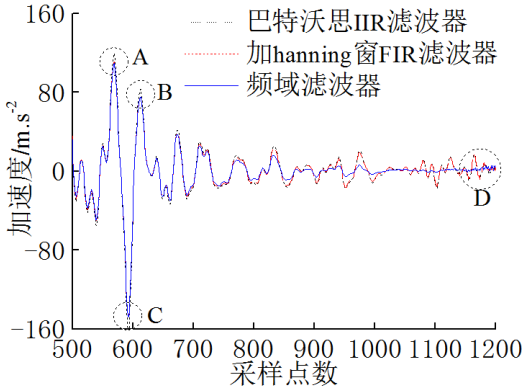
There exists zero shift of the measured signal due to the test equipment defects and external factors.

- 通过去除趋势项的方法可以有效的消除振动信号零漂或长周期趋势项干扰。

The zero shift problem can be solved by least square method.

## 3.3 振动信号预处理方法对比/ Comparison of digital filtering method



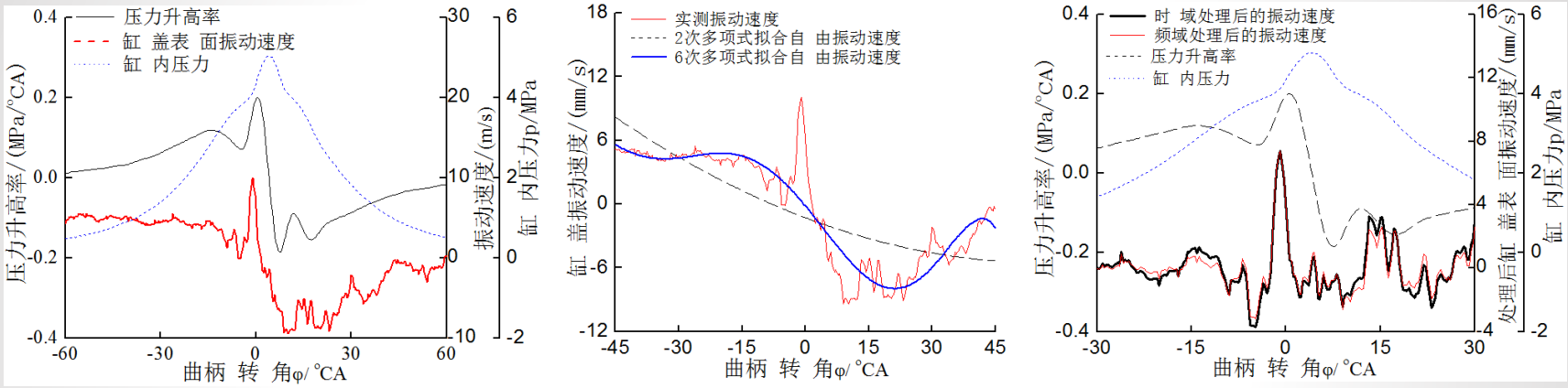




- 设计了IIR、FIR及频域滤波器对实测振动加速度信号进行对比，保留与燃烧密切相关的信息。

Different types of digital filtering method were designed to remove the interfering component.

# 4. 基于振动信号的燃烧参数提取/Combustion parameter extraction from vibration

## 4.1 振动速度信号预处理/ Pretreatment of vibration velocity




- 根据压升率曲线能够得到燃烧起始时刻及最大压升率出现时刻等燃烧表征参数；

The start timing of combustion and appearance timing of PIR can be obtained from PIR.

- 振动速度信号包含约束支架振动的影响，可以通过去除趋势项或滤波方法有效去除约束支架的影响，进而用于提取燃烧表征参数。

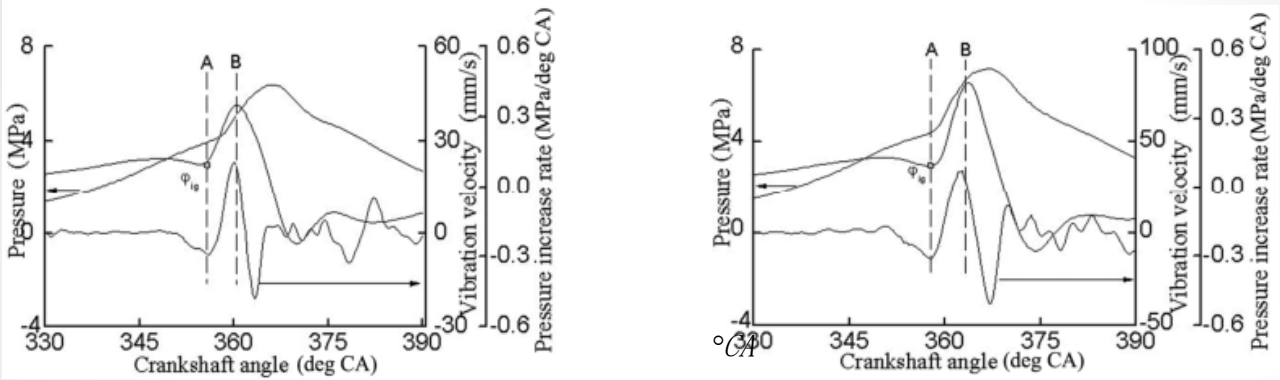
Vibration velocity is affected by the vibration of fixing bracket.

The influence of fixing bracket can be removed by least square method or digital filtering method.

# 4. 基于振动信号的燃烧参数提取/Combustion parameter extraction from vibration

## 4.2 基于振动速度信号的燃烧参数提取：单缸机

**Application for single-cylinder engine**




| | Pressureincrease rate | Vibrationvelocity |
|---|---|---|
| Point A | 355.5 | 356.0 |
| Point B | 361.0 | 360 |
| Point A | 357.5 | 358.0 |
| Point B | 363.5 | 362.5 |

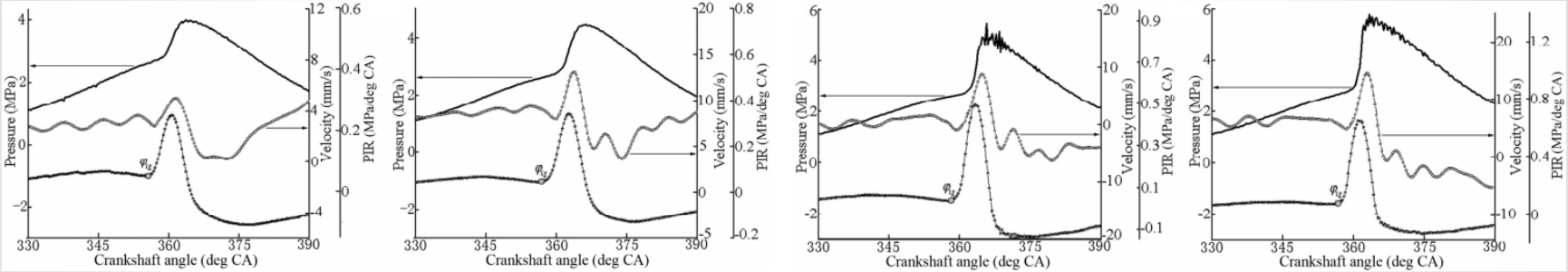
- 利用处理后的振动速度信号对燃烧起始时刻及最大压升率出现时刻进行分析，误差在1°CA以内。

**The treated vibration velocity is used to estimate the start timing of combustion and appearance timing of peak PIR.**

**The estimation result is verified with PIR and the error is smaller than 1 ° CA.**

# 4. 基于振动信号的燃烧参数提取/Combustion parameter extraction from vibration

## 4.2 基于振动速度信号的燃烧参数提取：两缸机 Application for 2-cylinder engine




| Working condition | Timings of the start of combustion calculated from the following curves (deg CA) | | Angular deviation (deg CA) |
|---|---|---|---|
| | Pressureincrease rate | Vibrationvelocity | |
| 1400 r/min, 10 N m | 353.5 | 354.0 | 0.5 |
| 1400 r/min, 15 N m | 357.3 | 358.4 | 1.1 |
| 1400 r/min, 20 N m | 357.9 | 358.7 | 0.8 |
| 1400 r/min, 25 N m | 356.4 | 357.6 | 1.2 |

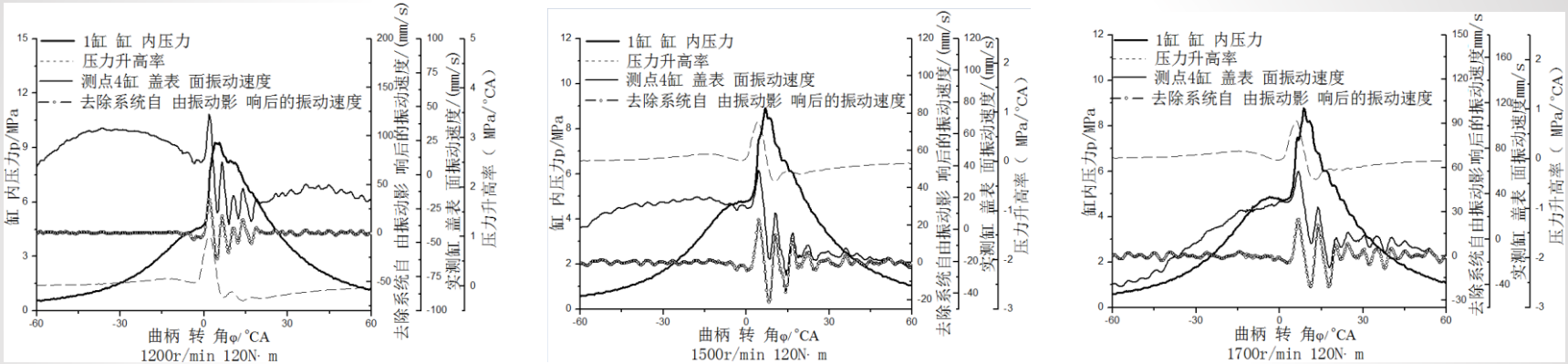
- 利用振动速度信号对两缸HCCI发动机四种不同工况下的燃烧起始时刻进行分析，不同工况的误差在1.5°CA以内

**Vibration velocity was used to estimate the start timing of combustion for a 2-cylinder HCCI engine.**

**The error is within 1.5 ° CA in the experiment.**

# 4. 基于振动信号的燃烧参数提取/Combustion parameter extraction from vibration

## 4.3 基于振动速度信号的燃烧参数提取：495柴油机 Application for 495 diesel engine




- 利用振动速度信号得到的燃烧始点滞后于根据压力升高率识别得到的燃烧始点，滞后角度在1.2°CA-3.0 °CA之间；

The estimated start timing of combustion is later than the true value about 1.2-3.0 ° CA

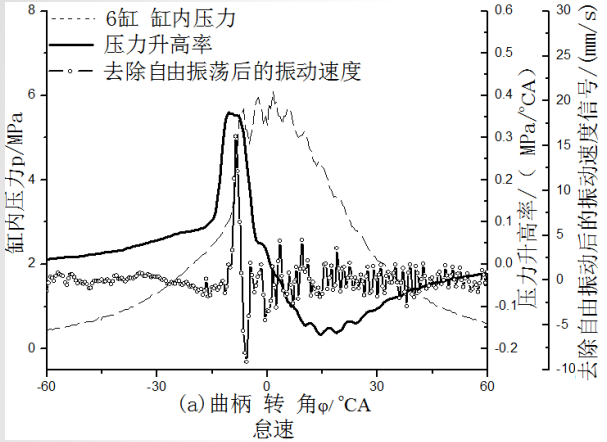
- 以滞后角度区间的平均值2.1°CA作为系统偏差，则识别误差在±0.9°CA以内。

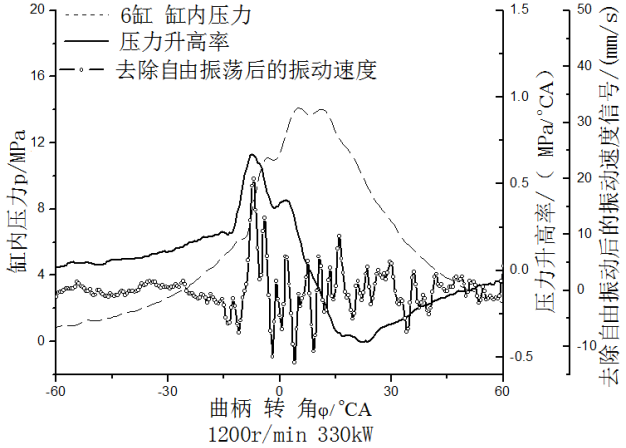
The average of deviation range (2.1 ° CA) is considered as the systematic deviation.

The estimation accuracy for start timing of combustion with vibration velocity is within ±0.9° CA.

# 4. 基于振动信号的燃烧参数提取/Combustion parameter extraction from vibration

## 4.4 基于振动速度信号的燃烧参数提取：6190柴油机 Application for 6190 diesel engine




| 工况 | 滞后偏差 |
|---|---|
| 怠速 | 4.3 |
| 800r/min 空载 | 3.9 |
| 1000 r/min 空载 | 4.5 |
| 1200 r/min 50kW | 5.2 |
| 1200 r/min 165 kW | 3.2 |
| 1200 r/min 248 kW | 4.6 |
| 1200 r/min 297 kW | 4.5 |
| 1200 r/min 330 kW | 3.1 |

- 利用振动速度信号得到的燃烧始点同样滞后于根据压力升高率识别得到的燃烧始点；

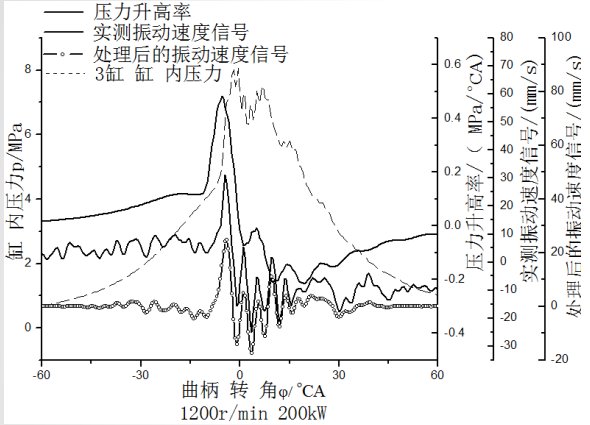
The estimated start timing of combustion from vibration velocity is also later than the true value obtained from PIR

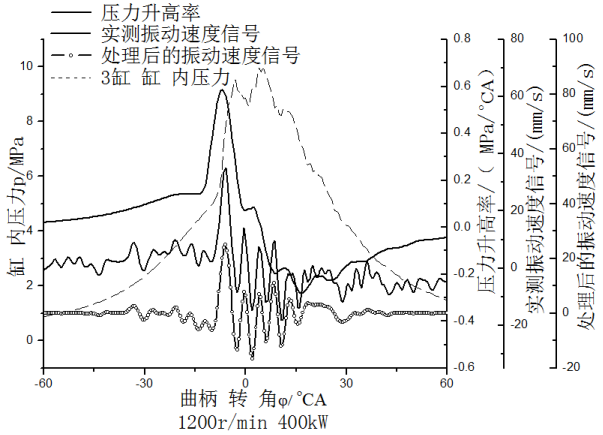
- 以滞后角度区间的平均值4.1°CA作为系统偏差，则识别误差在±1°CA以内。

The average of deviation range (4.1 ° CA) is considered as the systematic deviation and the estimation accuracy for start timing of combustion is within ±1° CA.

# 4. 基于振动信号的燃烧参数提取/Combustion parameter extraction from vibration

## 4.5 基于振动速度信号的燃烧参数提取：12V190柴油机 Application for 12V190 diesel engine




| | 滞后偏差 |
|---|---|
| 1000r/min 空载 | 3.8 |
| 1200 r/min 空载 | 3.8 |
| 1200 r/min 100kW | 3.8 |
| 1200 r/min 200 kW | 3.8 |
| 1200 r/min 300 kW | 2.3 |
| 1200 r/min 400 kW | 2.5 |
| 1500 r/min 空载 | 3.3 |
| 1500 r/min 150 kW | 2.0 |
| 1500 r/min 300 kW | 4.4 |
| 1500 r/min 450 kW | 3.8 |
| 1500 r/min 675 kW | 2.0 |
| 1500 r/min 880 kW | 3.3 |
| 1500 r/min 1000 kW | 3.4 |

- 以滞后角度区间的平均值3°CA作为系统偏差，则识别误差在±1.5°CA以内。

The average of deviation range (3 ° CA) is considered as the systematic deviation and the estimation accuracy for start timing of combustion is within ±1.5° CA.

# 致谢

Thanks for Listening

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