第十一届内燃机可靠性技术国际研讨会

The 11th International Symposium on internal combustion engine reliability technology

内燃机故障智能监测预警方法与系统应用

Intelligent monitoring and warning method for internal combustion engine faults and the system applications

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内燃机故障智能监测预警方法与系统应用

Intelligent monitoring and warning method for internal combustion engine faults and the system application

01 内燃机故障监测诊断研究背景

Research background of internal combustion engine fault monitoring and diagnosis

02 内燃机多源信号与特征指标

Multi-sources signals and characteristics of internal combustion engine

03 内燃机智能预警诊断方法

Intelligent warning and diagnosis methods of internal combustion engine

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On-line monitoring and diagnosis system of internal combustion engine

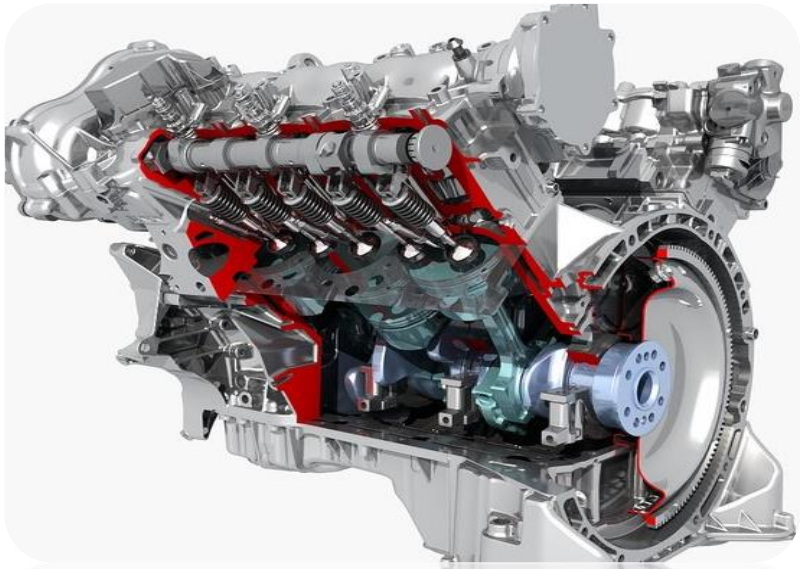
01

内燃机故障监测诊断研究背景

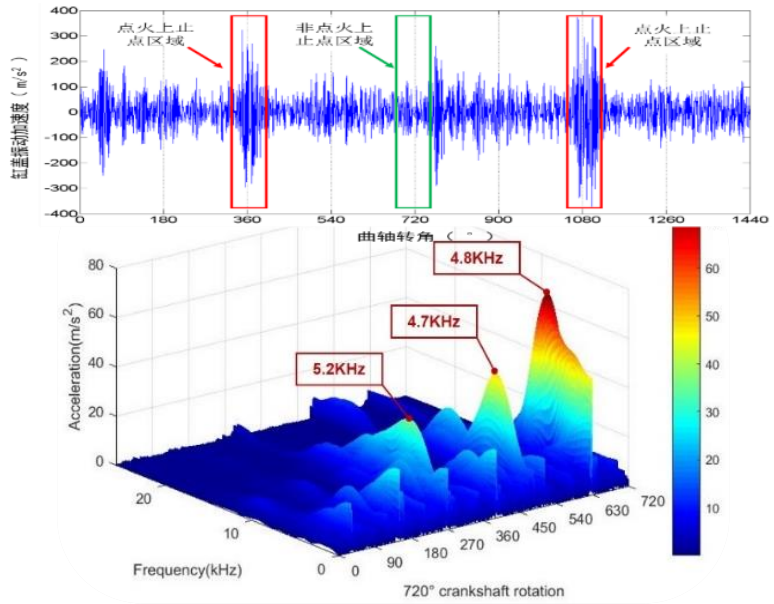
Research background of internal combustion engine fault monitoring and diagnosis

01 研究背景 Research background

活塞式发动机实际应用



发动机内部结构复杂紧凑



壳体振动信号时域、频域图

船舶柴油内燃机

运行需求：多变工况下稳定运行

核电应急柴油内燃机

运行需求：规定短时间内应急启动

- **多变运行工况：变转速、变负荷、变环境**
- **复杂紧凑结构：缸数多、动件多、激励多**
- **壳体振动信号：强干扰、弱特征、强耦合**

01 研究背景 Research background

常见故障1：缸内失火

研究难点意义：最常见故障，易受工况改变而误判；缺少缸温情况下诊断难度大

Common fault 1: cylinder misfire

Significance of research difficulties: the most common fault has a wide application prospect and is easy to be misjudged by the change of working conditions

常见故障2：气门故障

研究难点意义：故障特征具有渐变性，故障前期特征不明显，易受工况改变而误判。

Common fault 2: valve failure

Significance of research difficulties: the fault characteristics are gradual and difficult to identify in the early stage of fault, and it is easy to be misjudged by the change of working conditions

常见故障3：连杆轴瓦故障

研究难点意义：故障特征具有渐变性，故障前期产生冲击弱，难以识别，监测诊断难度大。

Common fault 3: connecting rod bearing bush fault

Significance of research difficulties: the fault characteristics are gradual, and the impact in the early stage of the fault is weak, which is difficult to identify.

02 内燃机多源信号与特征指标

Multi-sources signals and characteristics of internal combustion engine

键相信号 Key-phase Signal

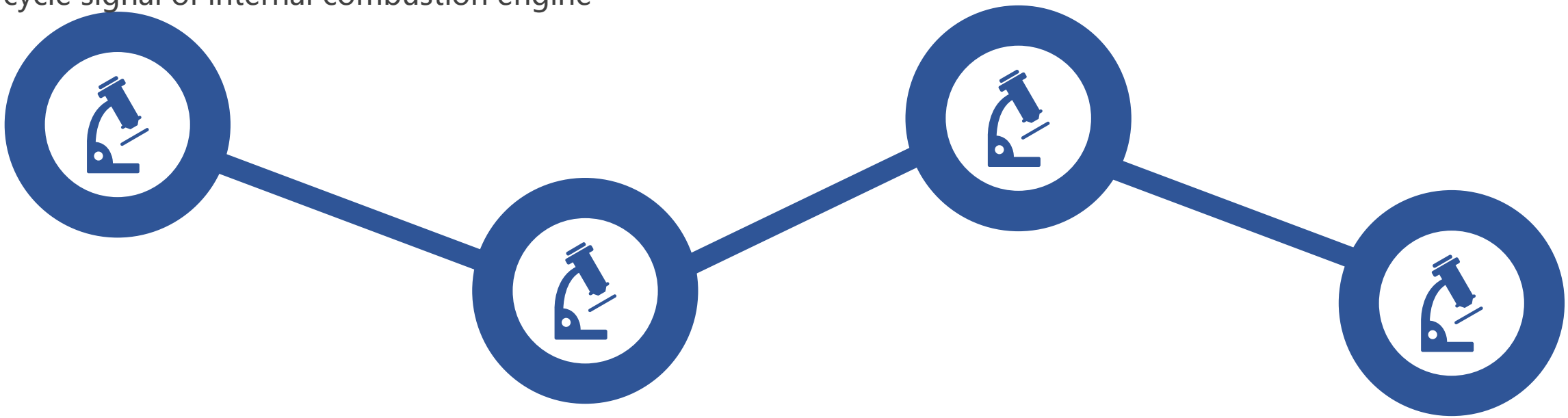
作用：内燃机整周期信号截取基础

Function: the basis for intercepting the whole cycle signal of internal combustion engine

瞬时转速信号 Instantaneous speed signal

作用：各类故障分析基础

Function: basis of various fault analysis



振动信号 Vibration signal

作用：各类故障分析基础

Function: basis of various fault analysis

其他信号 Other signal

作用：各类故障辅助分析

Function: Auxiliary Analysis of various faults

键相信号 Key-phase Signal

作用：内燃机整周期信号截取基础

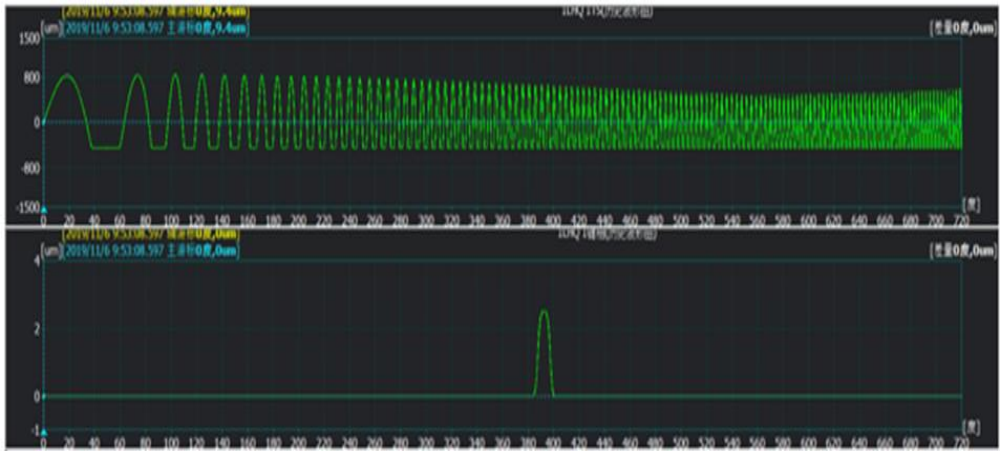
具体：电涡流传感器位移信号

主要特征分析：峰值数量-位置分析

Function: the basis for intercepting the whole cycle signal of internal combustion engine

Specific: displacement signal of eddy current sensor

Main characteristic analysis: peak number position analysis



键相信号示意图

瞬时转速信号 Instantaneous speed signal

作用：各类故障分析基础

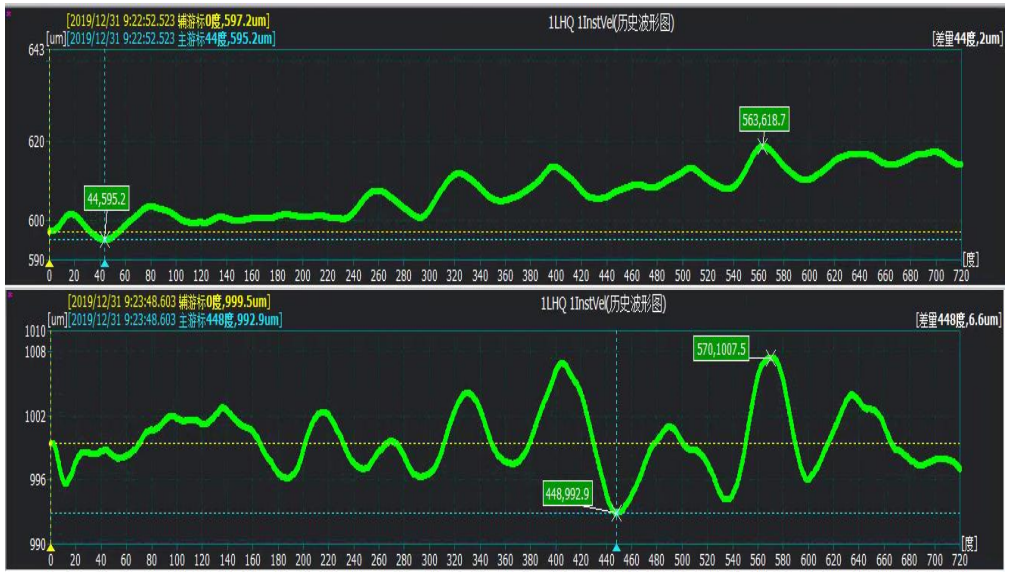
具体：电涡流传感器位移信号，计算频谱信号

主要特征分析：峰值相关，特定区间能量比

Function: basis of various fault analysis

Specifically: eddy current sensor displacement signal and calculate the spectrum signal

Main characteristic analysis: peak correlation, specific interval energy ratio



瞬时转速信号示意图，转速不稳定（上），稳定（下）

振动信号 Vibration signal

作用：各类故障分析基础

具体：压电传感器加速度信号，积分计算速度信号

包括：缸盖振动信号；箱体振动信号；

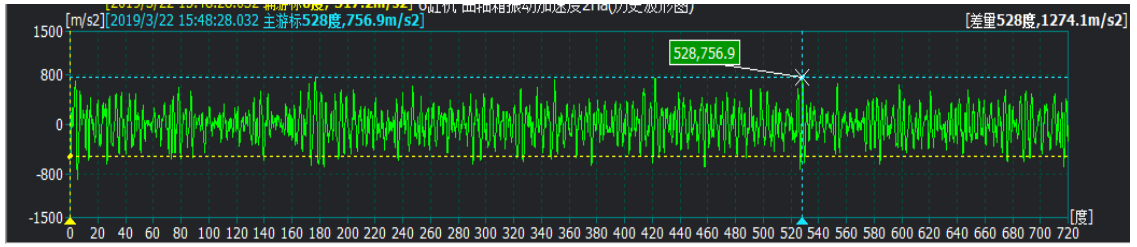
主要特征分析：峰值相关，特定区间能量比，特定指标（歪度，峭度），特定人工指标（做功能力）...

Function: basis of various fault analysis

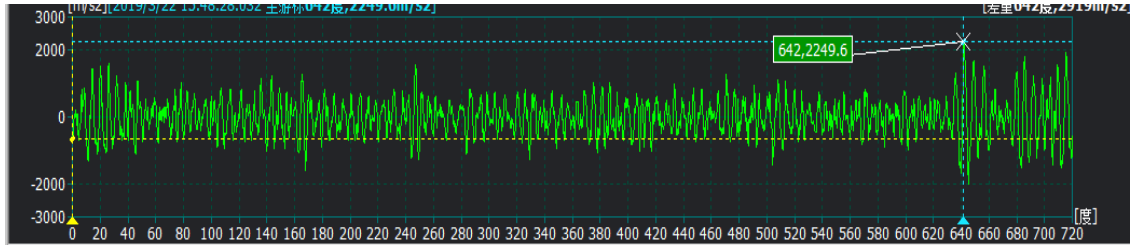
Specifically: piezoelectric sensor acceleration signal, integral calculation speed signal

Including: cylinder head vibration signal; Box vibration signal

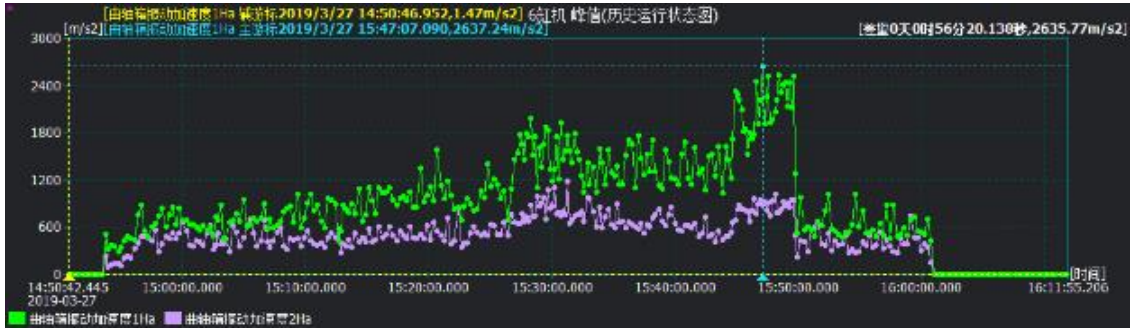
Main characteristic analysis: peak correlation, specific interval energy ratio, specific index (skewness, kurtosis), specific artificial index (work ability)



箱体振动信号 （正常）



箱体振动信号（故障，异常增大）



箱体振动峰值趋势信号（1号绿，2号紫）

振动信号 Vibration signal

作用：各类故障分析基础

具体：压电传感器加速度信号，积分计算速度信号

包括：缸盖振动信号；箱体振动信号；

主要特征分析：峰值相关，特定区间能量比，特定指标（歪度，峭度），特定人工指标（做功能力）...

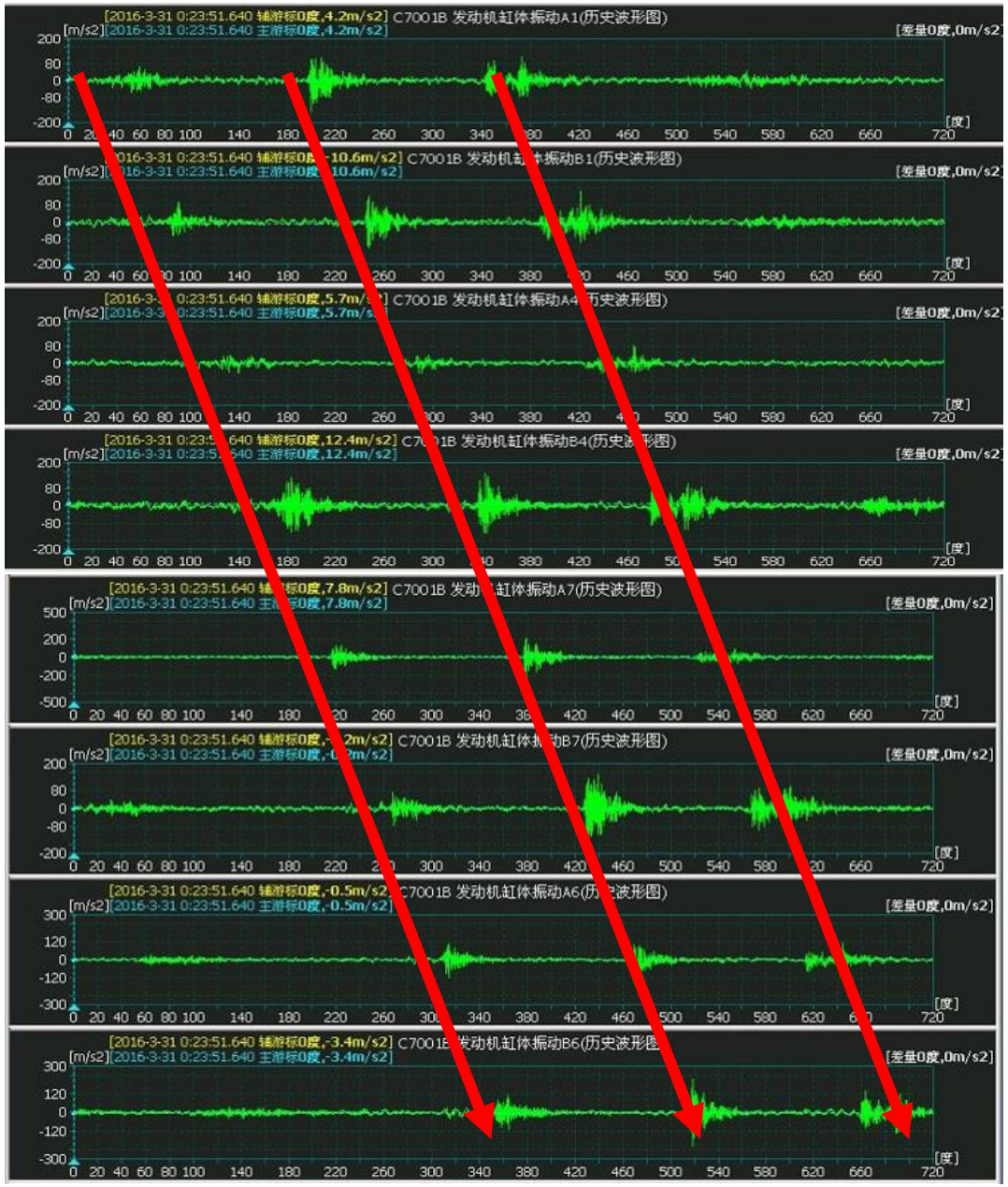
Function: basis of various fault analysis

Specifically: piezoelectric sensor acceleration signal, integral calculation speed signal

Including: cylinder head vibration signal; Box vibration signal

Main characteristic analysis: peak correlation, specific interval energy ratio, specific index (skewness, kurtosis), specific artificial index (work ability)

Multi cylinder continuous vibration waveform



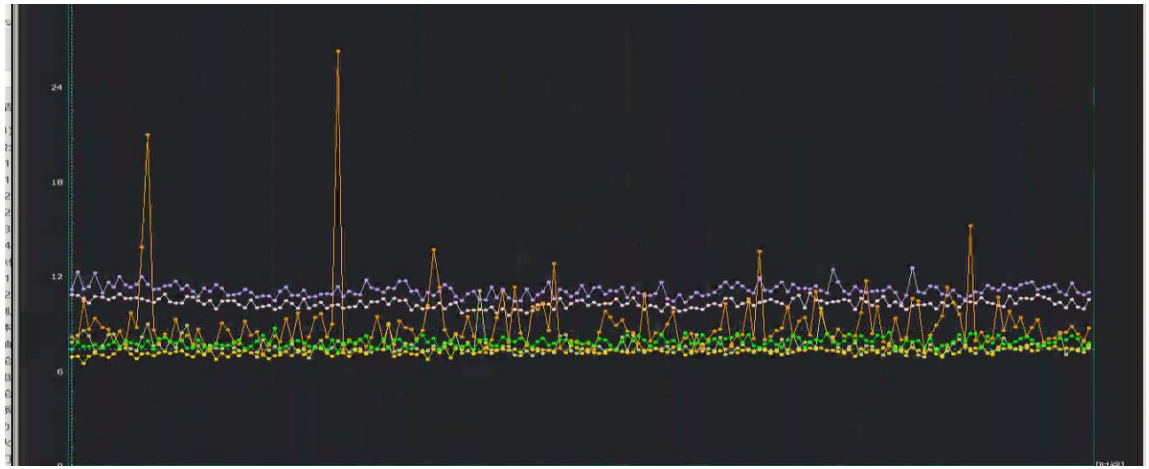
多缸连续振动波形

其他信号 Other signal

作用：故障辅助分析
具体：温度信号，油液信号，...
主要特征分析：温度值趋势，油品、磨粒值趋势

Function: auxiliary fault analysis
Specific: temperature signal, oil signal,
Main characteristic analysis: temperature value trend, oil and abrasive value trend

随开机温度升高趋势图



开机一段时间温度稳定趋势图

03 内燃机智能预警诊断方法

Intelligent warning and diagnosis methods of internal combustion engine

03 诊断方法 diagnosis method

1 特征分析 Feature analysis

分析内容:
人工分析：特征趋势与故障的关联

Analysis content:
Manually analyze the correlation between characteristic trend and fault

2 深度学习 Deep Learning

分析内容:
深度网络：挖掘故障的深层次自适应特征

Analysis content:
Depth network : mining deep adaptive features of faults

3 数字孪生 Digital twin

分析内容:
实际监测数据与模型数据之间的结合：获得机组实时状态，通过模型仿真进行机组未来状态的预测

Analysis content:
Combination between actual monitoring data and model data: obtain the real-time state of the unit, and predict the future state of the unit through model simulation

分析对象 Analysis object

缸内失火 cylinder misfire

气门间隙 valve clearance

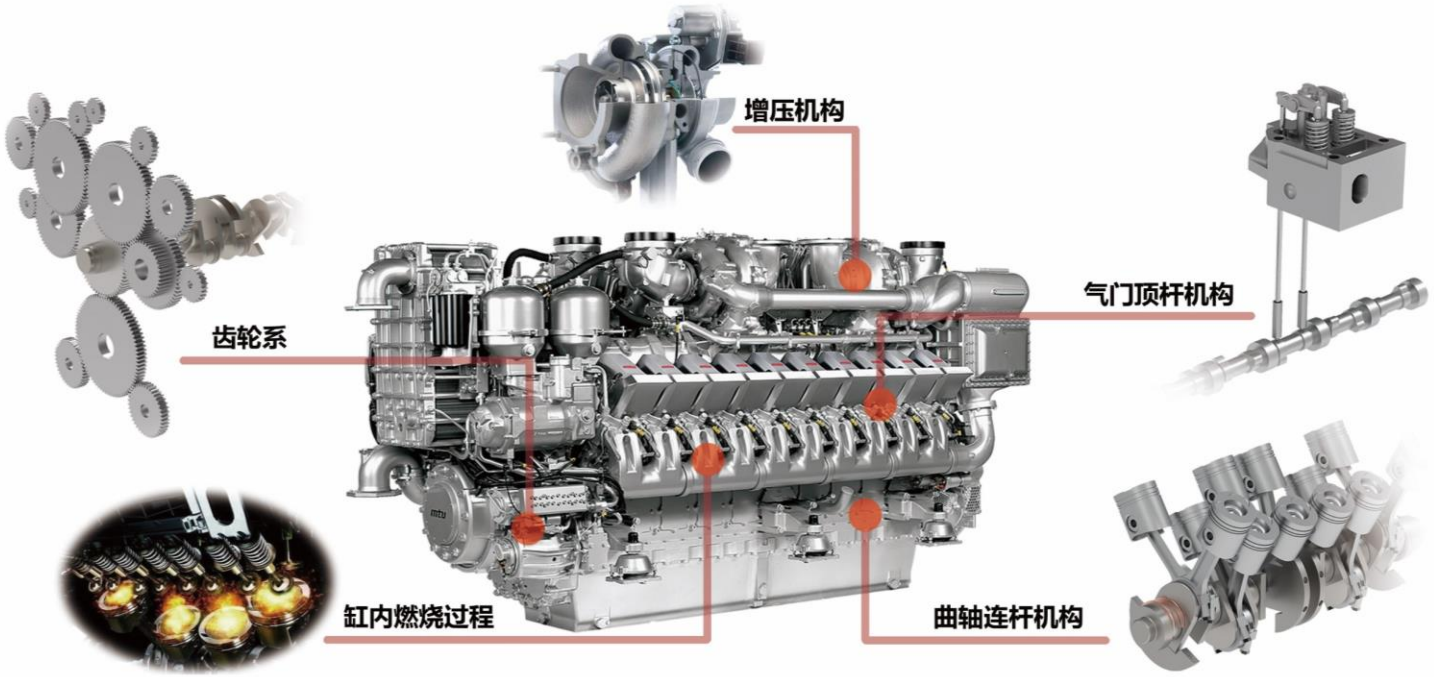
轴瓦磨损 Bearing bush failure

诊断方法 diagnosis method

特征分析 Feature analysis

深度学习 Deep Learning

数字孪生 Digital twin



柴油机壳体振动信号

深度学习 Deep Learning

解决内燃机诊断问题 Solve the problem

1、卷积神经网络：包括卷积层和池化层，是主要的特征提取网络。代表性的卷积神经网络包括LeNet-5、VGG、AlexNet

Convolution neural network includes convolution layer and pooling layer, which is the main feature extraction network. Representative convolutional neural networks include LeNet-5、VGG、AlexNet.

添加自适应特征改善人工特征不完备问题

Adding adaptive features to improve the problem of incomplete artificial features

2 、循环神经网络更擅长于具有时序上联系的样本的处理，是主要的分析特征前后关联性网络，代表性的如RNN，LSTM

Recurrent neural network neural network is better at processing samples with time series connection. It is the main correlation network before and after analysis features, such as RNN and LSTM

从时序角度出发更好的处理内燃机序列变化的数据

From the perspective of timing, better deal with the data of internal combustion engine sequence change

深度学习 Deep Learning

3、生成对抗网络双方为判别模型和生成模型。通过判别模型和生成模型两个神经网络的对抗训练，有效地生成符合真实数据分布的新数据。代表性的如GAN

The two sides of generative adversarial network are discrimination model and generation model. Through the confrontation training of two neural networks, discriminant model and generative model, new data in line with the real data distribution can be effectively generated. Representative such as GAN

4、注意力机制，注意力机制的主要作用为通过分配注意力系数，使得可视化故障特征与源样本之间的关联成为可能。

Attention mechanism. The main function of attention mechanism is to make it possible to visualize the correlation between fault features and source samples by allocating attention coefficients

解决内燃机诊断问题 Solve the problem

添加生成样本改善内燃机故障小样本或样本平衡问题

Adding generated samples to improve the problem of small sample or sample balance of internal combustion engine fault

分配注意力系数，可视化内燃机故障与信号角域关联性。

Assign attention coefficient to visualize the correlation between internal combustion engine fault and signal angle domain.

数字孪生 Digital twin

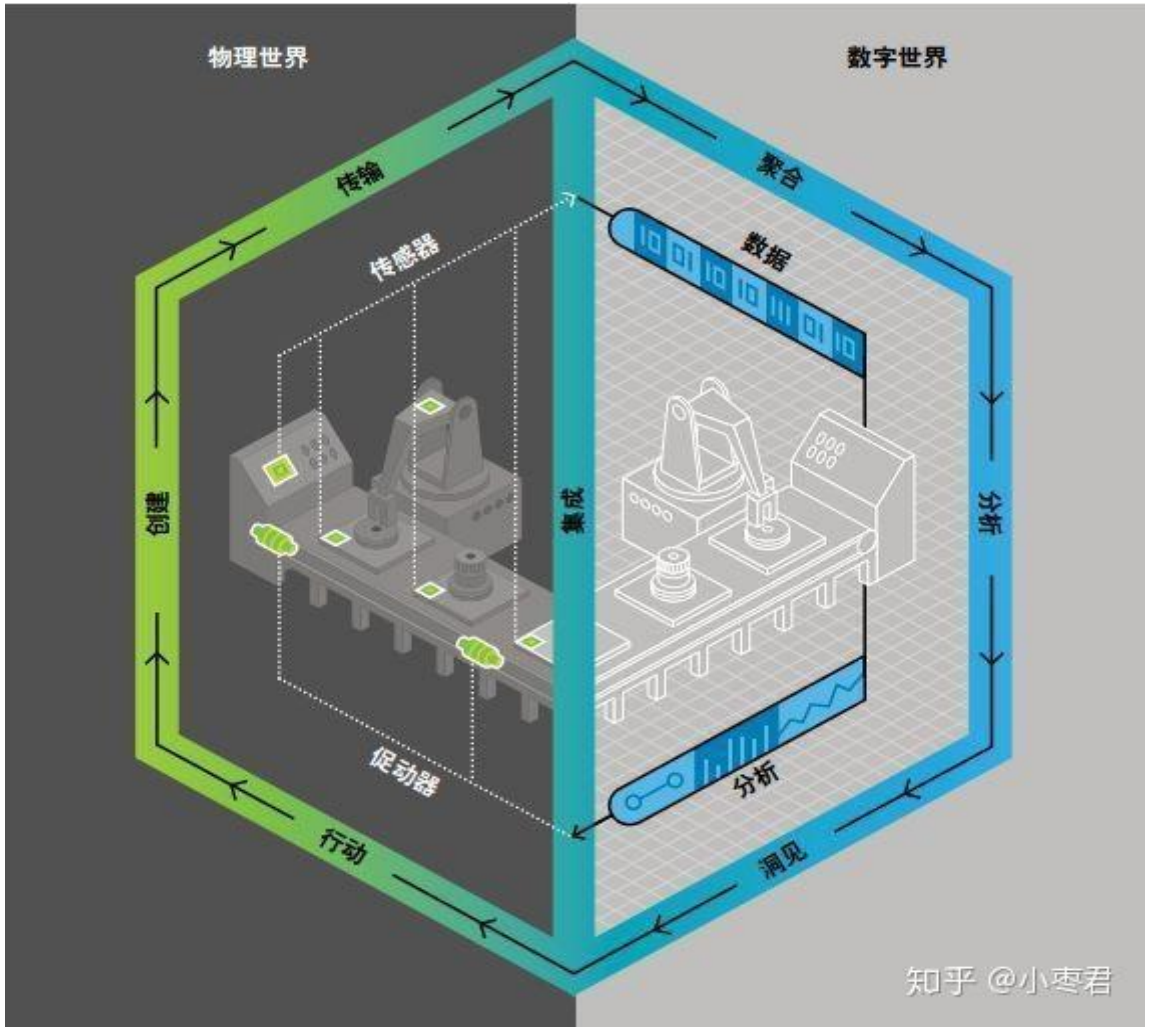
1、基于实测数据，建立仿真模型。
Based on the measured data, the simulation model is established.

2、实机开展故障试验，模型模拟故障运行。
Carry out fault test on the real machine and simulate fault operation with the model.

3、实机实测故障结果，模型获取模拟结果。
The real machine measured the fault results, and the model obtained the simulation results.

4、修正仿真模型，得出故障机理
Modify the simulation model and get the fault mechanism

5、优化监测点，降低监测成本
Optimize monitoring points and reduce monitoring costs

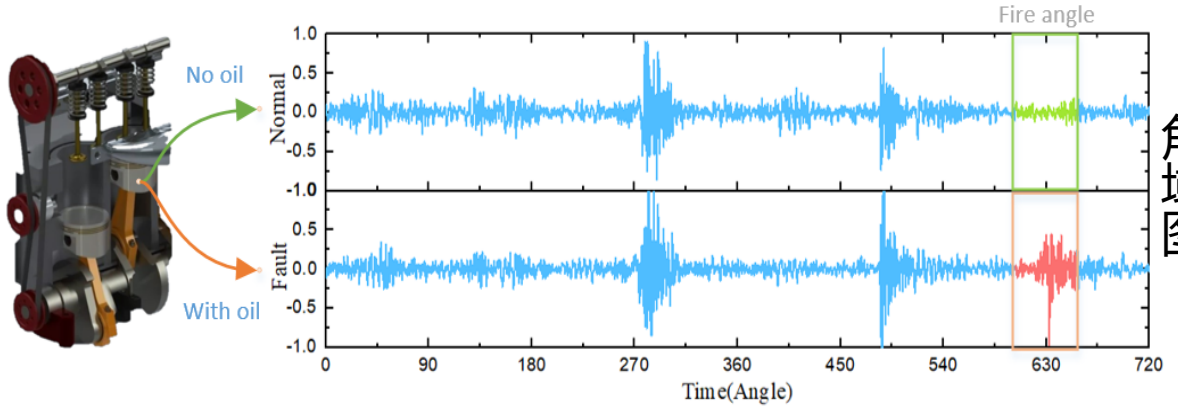


一、缸内失火 Common fault 1: cylinder misfire

（1）特征分析 Feature analysis

特征：发火区间预选取600~660度内振动烈度趋势

Features: vibration intensity trend within standard 600 ~ 660 degrees in the ignition section

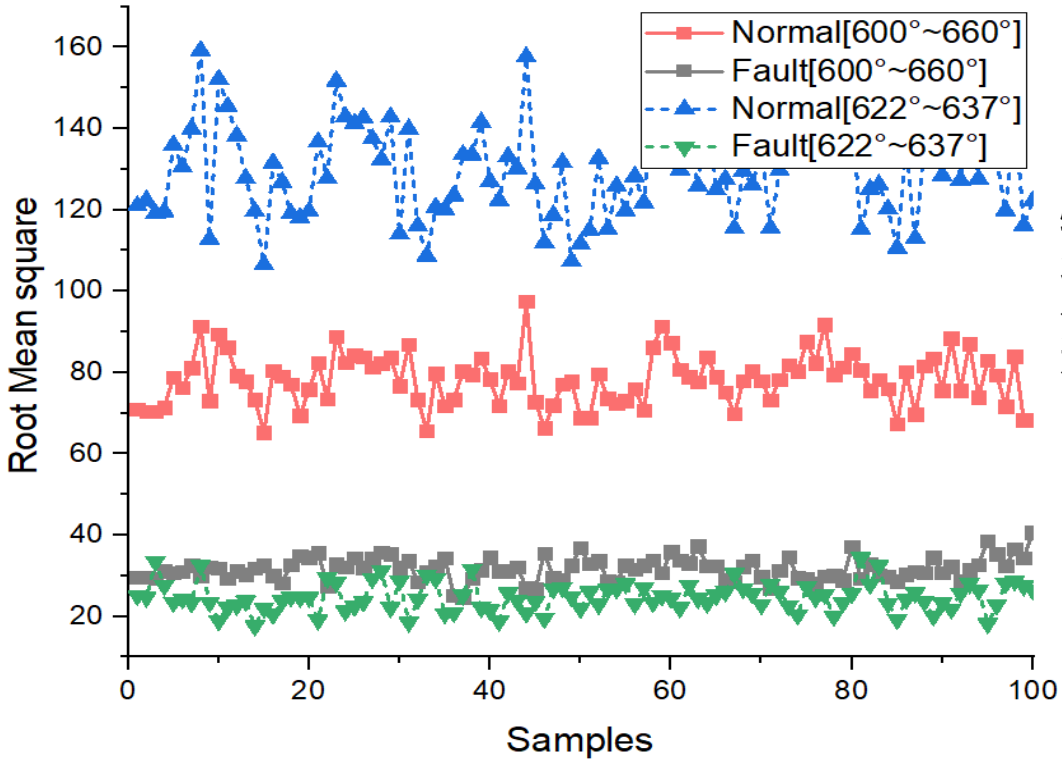


角域图

（2）深度学习 Deep Learning

特征：通过深度卷积网络与稀疏注意力机制结合，将故障发火区间缩小至622~637度。

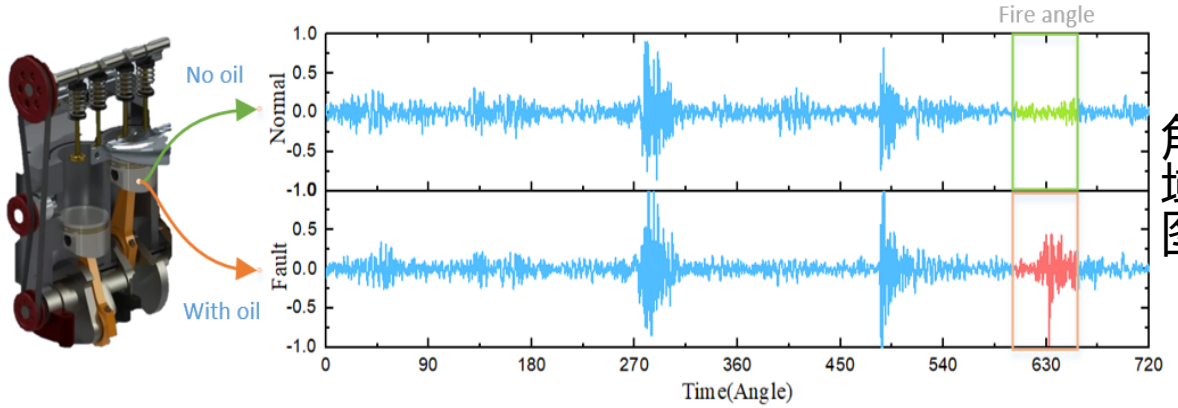
Features: through the combination of deep convolution network and sparse attention mechanism, the fault ignition interval is reduced to 622 ~ 637 degrees.



特征分布图

缸内失火 cylinder misfire

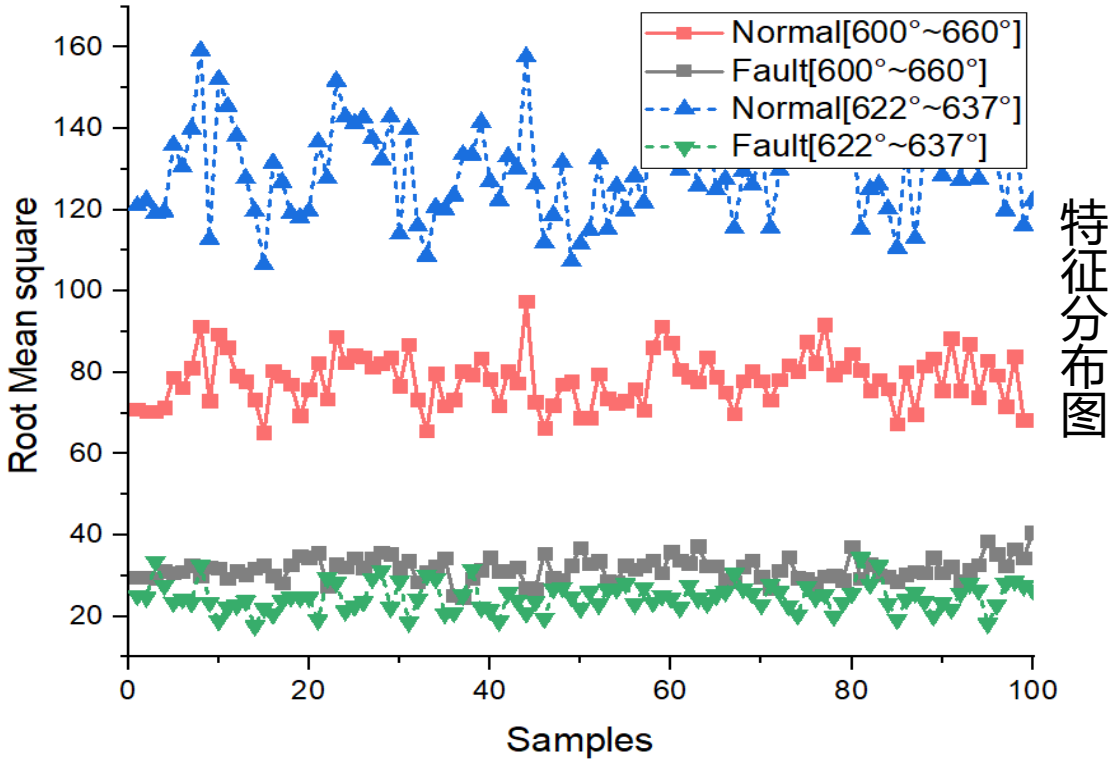
参考意义：由右下图可见，深度学习和数字孪生的引入，为一台机组准确划定失火故障所引起的故障角域，相比原预设角域，振动能量特征区分更为明显，降低了监测成本。



角域图

Reference significance:

As can be seen from the following figure on the right, the introduction of deep learning and digital twin can accurately delineate the fault angle domain caused by fire fault for a unit. Compared with the original preset angle domain, the vibration energy characteristics are more clearly distinguished, which reduces the monitoring cost.



特征分布图

气门间隙 valve clearance

特征分析 **深度学习**

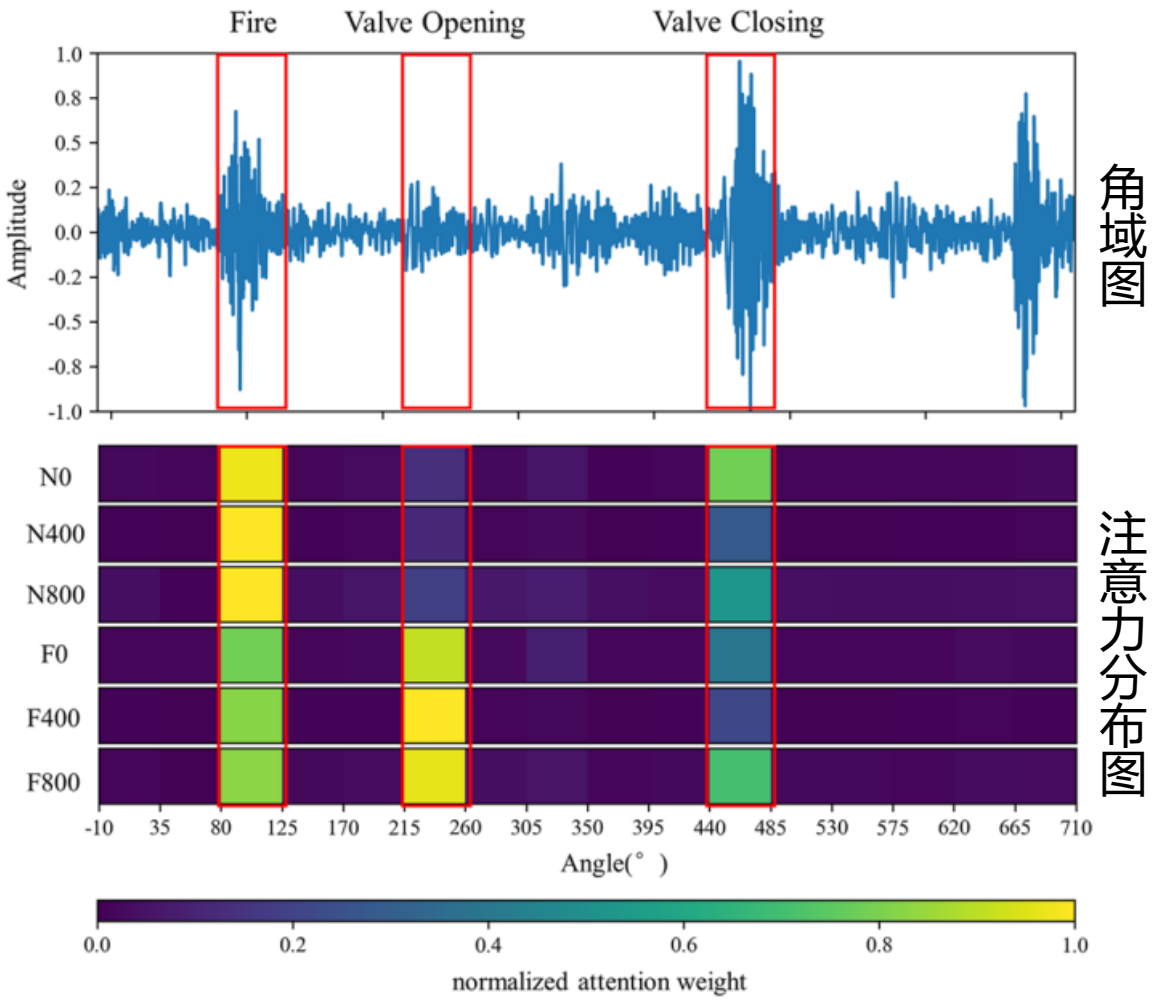
Feature analysis **Deep Learning**

特征：通过LSTM与注意力机制集合，得出气门间隙导致发火、气门开关相位出现异常

Features: LSTM and Attention mechanism. ignition caused by valve clearance and abnormal phase of valve switch

参考意义：对一台机组细致划分真实气门间隙所引起的故障区间，提高诊断精度，降低监测成本。

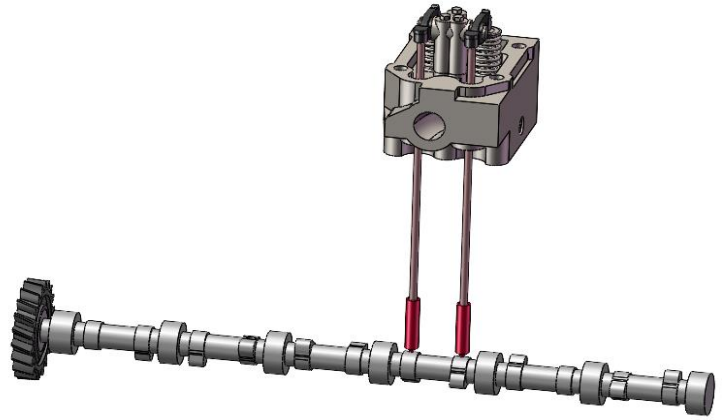
Reference significance:
For a unit, the fault interval caused by the real valve clearance is carefully divided to improve the diagnosis accuracy and reduce the monitoring cost.

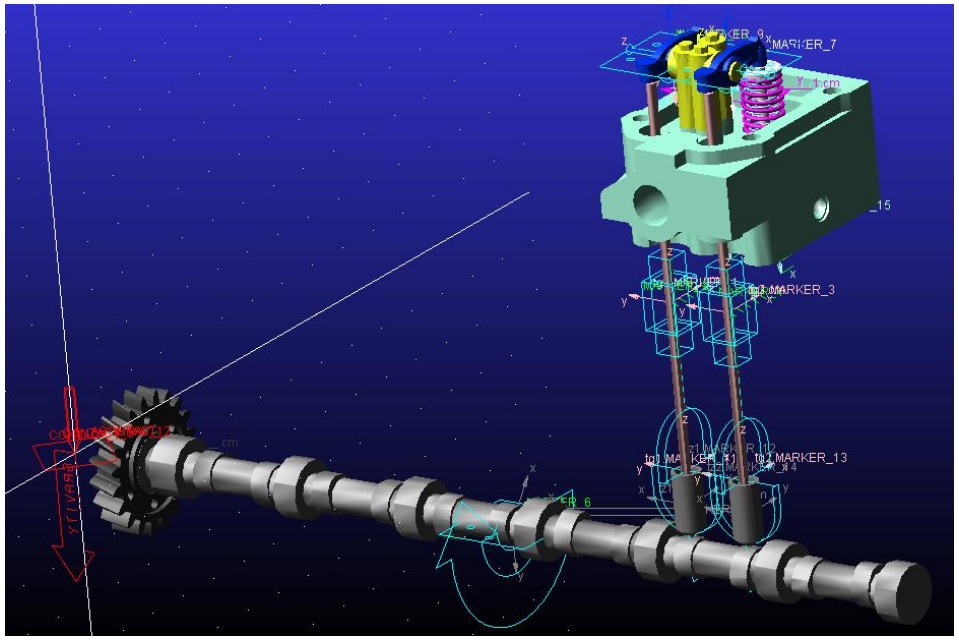


气门间隙 valve clearance

数字孪生 Digital twin

约束施加对象	施加约束副	Constraint application object	Constraint pair
凸轮轴与地面	转动副	Camshaft and ground	Rotating pair
凸轮轴与挺柱	接触副	Camshaft and tappet	Contact pair
挺柱与推杆	虎克铰	Tappet and push rod	Hooke
推杆与摇臂	接触副	Push rod and rocker arm	Contact pair
摇臂与缸盖	转动副	Rocker arm and cylinder head	Rotating pair
摇臂与气门盖	接触副	Rocker arm and valve cover	Contact pair
气门盖与气门	固定副	Valve cover and valve	Fixed pair
气门盖与缸盖	弹簧力	Valve cover and cylinder head	Spring force
气门与缸盖	滑动副	Valve and cylinder head	Sliding pair
缸盖与地面	固定副	Cylinder head and ground	Fixed pair





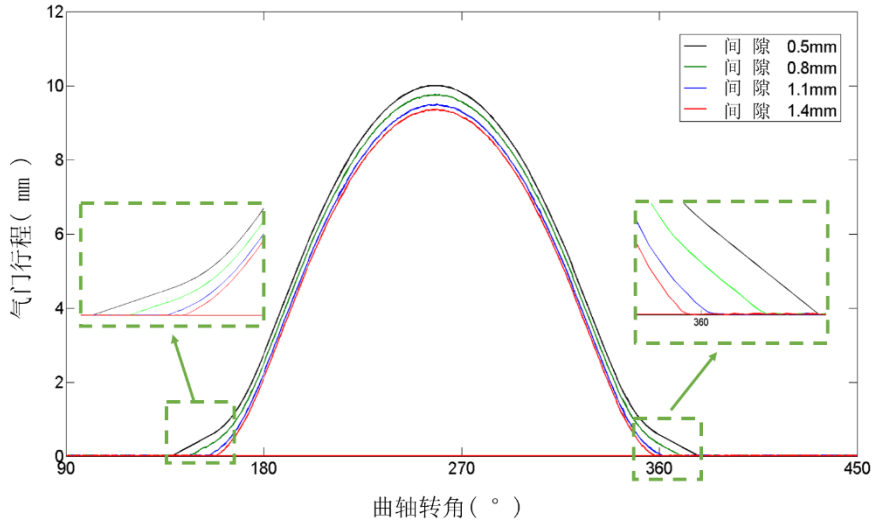
数字孪生 Digital twin

与正常状态相比，气门间隙异常增大后：
1、气门关闭冲击**振动幅值**显著**增加**
2、气门关闭冲击**相位**存在一定程度的**提前**

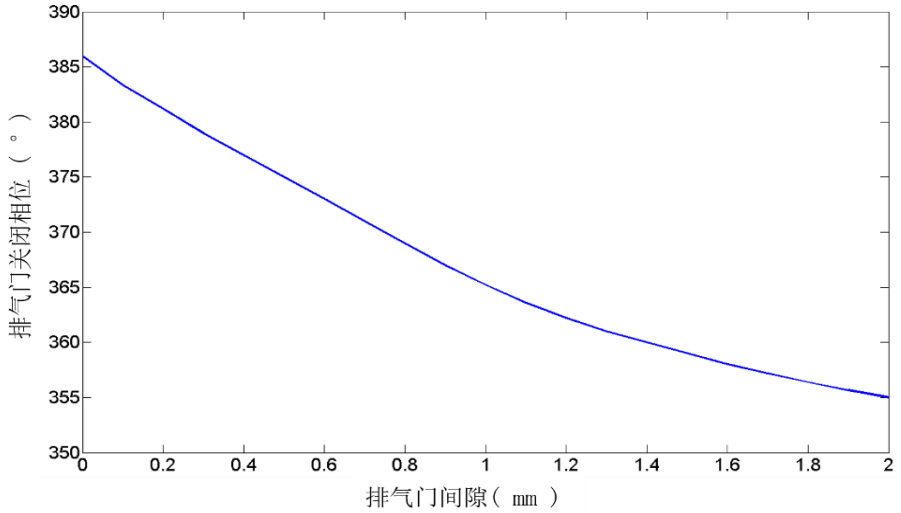
Compared with the normal state, after the abnormal increase of valve clearance:

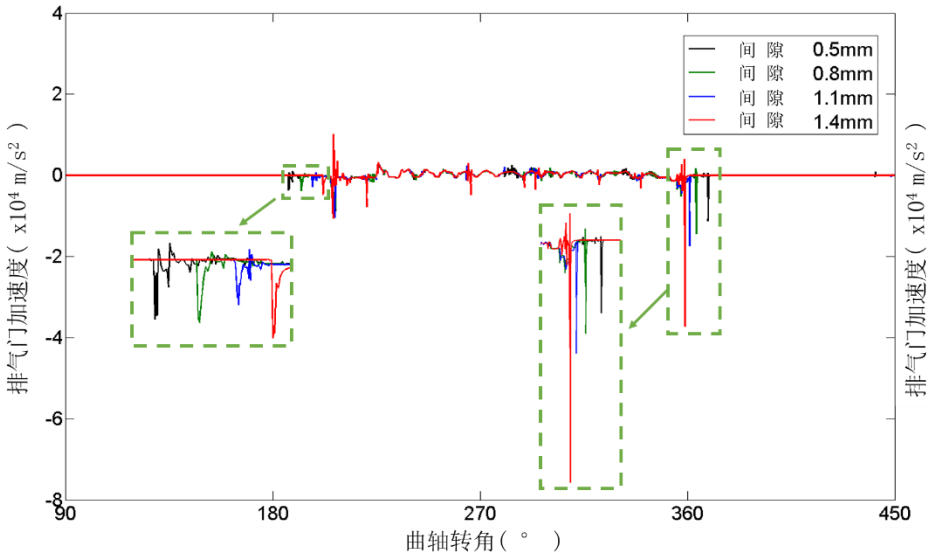
1.**The shock vibration amplitude of valve closing increases significantly**
2. **There is a certain advance in the impact phase of valve closing**

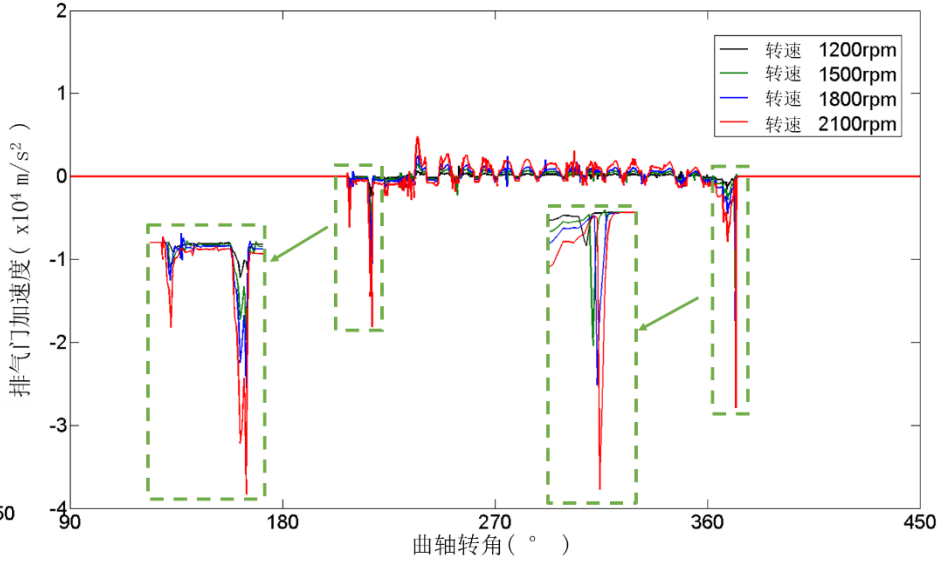
不同排气门间隙下的排气门升程曲仿真结果



排气门间隙和排气门关闭正时之间的变化曲线







轴瓦磨损 Bearing bush wear

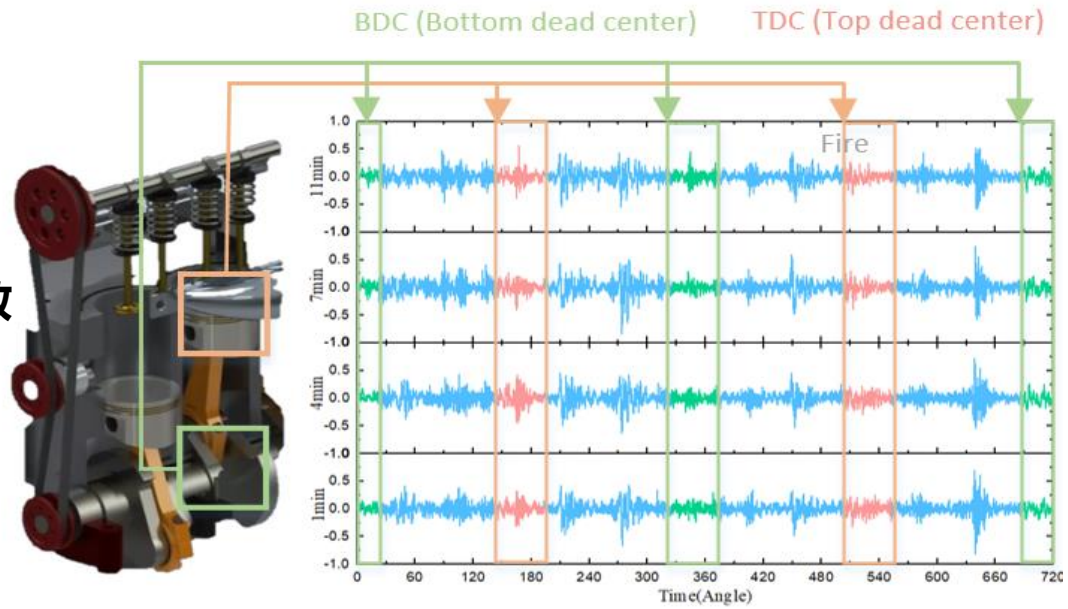
特征分析 深度学习

Feature analysis Deep Learning

特征：通过卷积网络，GAN与注意力机制结合，得出轴瓦导致上下止点冲击出现异常

Features:CNN、GAN and Attention mechanism.

Abnormal impact of upper and lower dead center caused by bearing bush

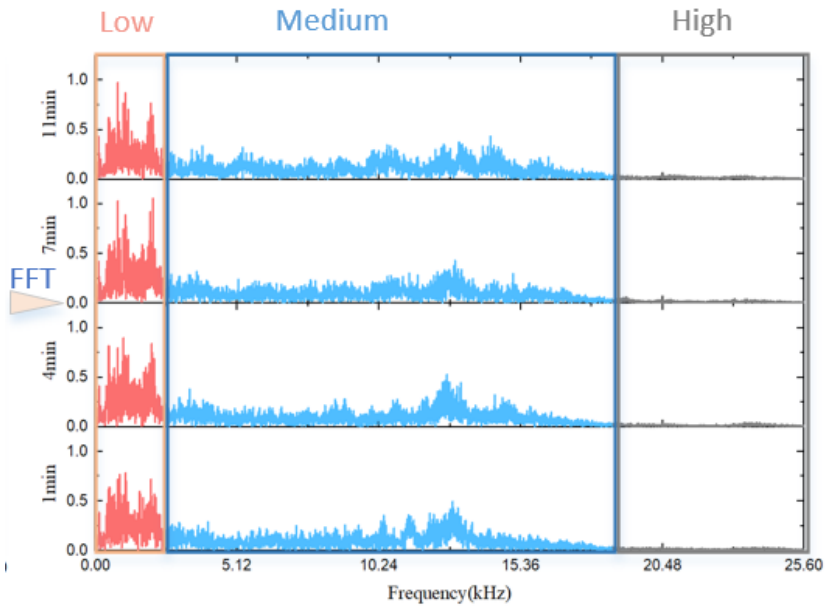


角域图

参考意义：对一台机组细致划分真实轴瓦磨损所引起的故障区间，提高诊断精度，降低监测成本，同时增加对该故障机理认知。

Reference significance:

For a unit, the fault interval caused by real bearing bush wear is carefully divided to improve the diagnosis accuracy, reduce the monitoring cost, and increase the understanding of the fault mechanism.



频域图

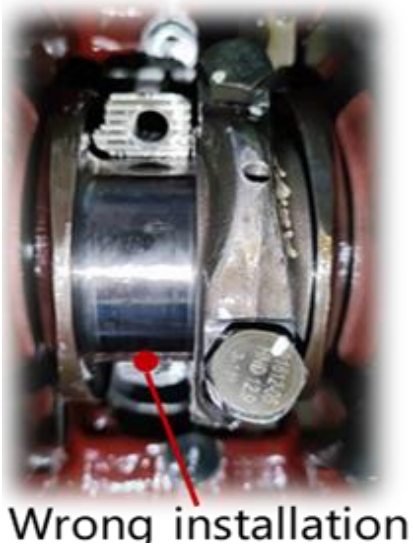
轴瓦磨损 Bearing bush wear

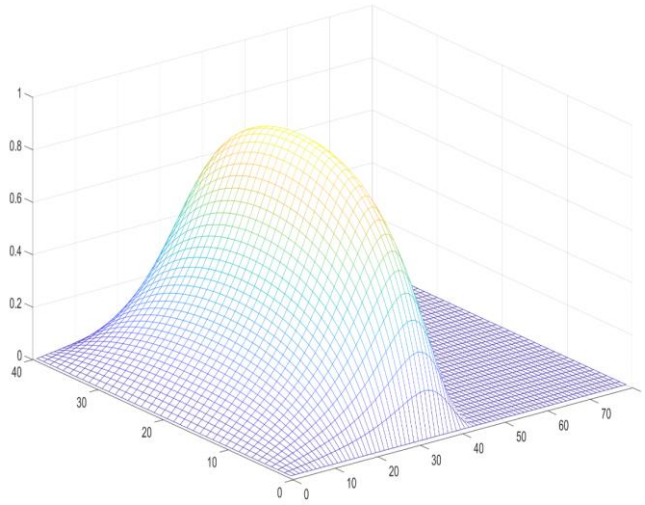
数字孪生

Digital twin

特征：运用数字孪生，可视化故障导致轴瓦油膜压力出现异常

Features: Digital twin . Abnormal impact of oil film pressure by bearing bush



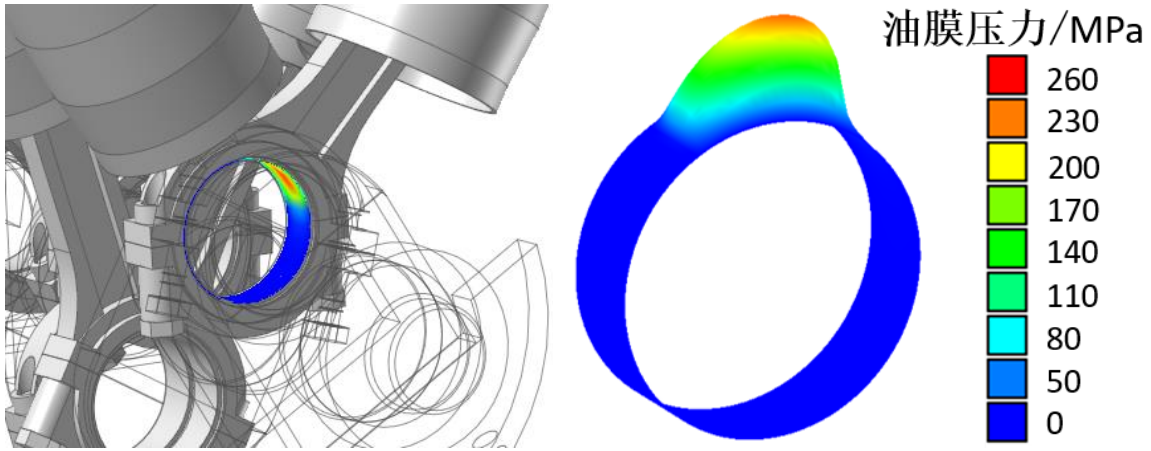


油膜压力分布图

参考意义：对一台机组细致划分真实的轴瓦磨损区间以及油膜压力分布，提高诊断精度，降低监测成本，同时增加对该故障机理认知。

Reference significance:

For a unit, the wear interval and oil film pressure distribution by real bearing bush wear is carefully divided to improve the diagnosis accuracy, reduce the monitoring cost, and increase the understanding of the fault mechanism.



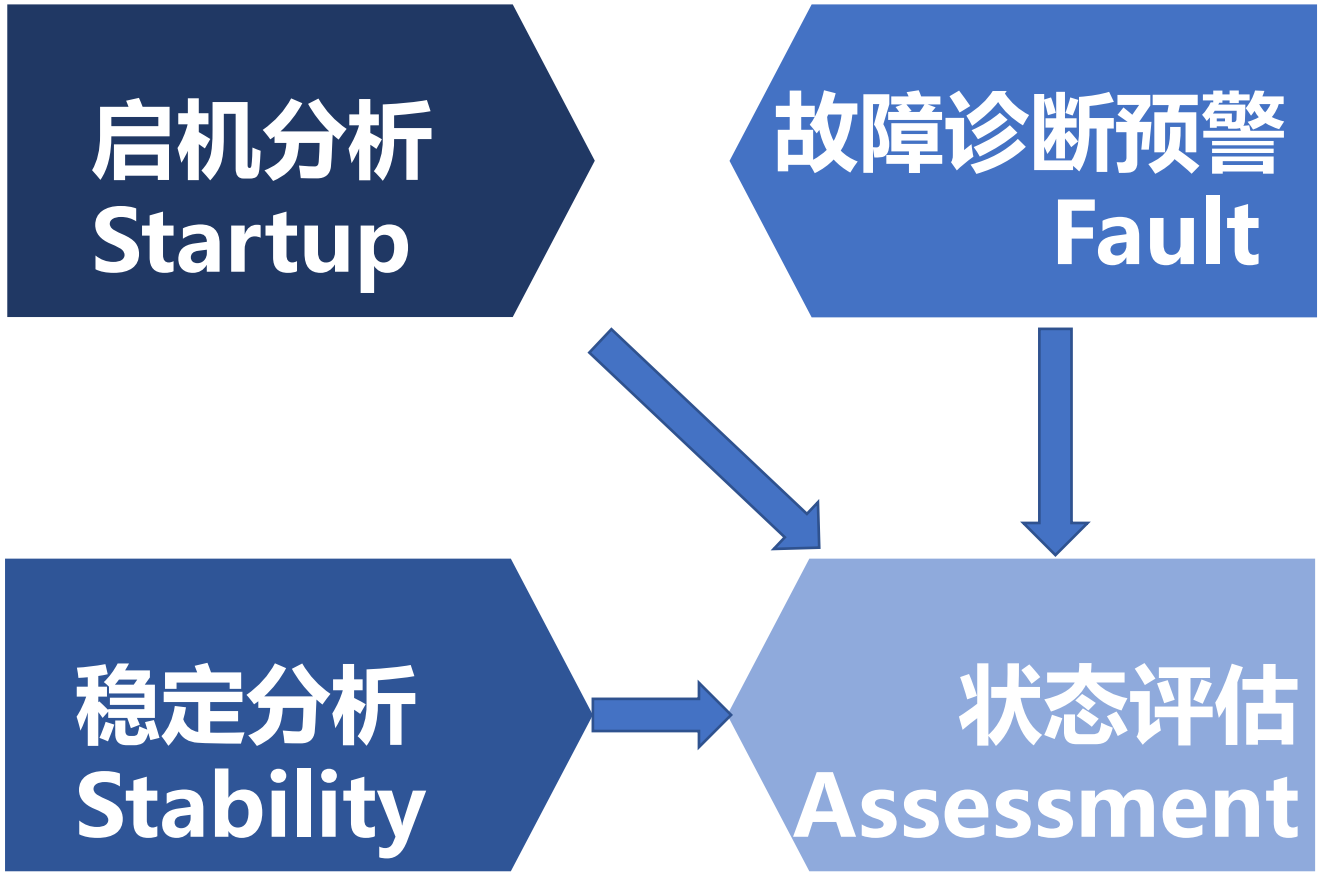
04 内燃机在线监测诊断系统

On-line monitoring and diagnosis system of internal combustion engine

01

启机分析

满足特别是核电柴油机的启机要求标准



03

故障诊断预警

故障预警，降低柴油机故障造成的损失的概率

02

稳定分析

满足多数柴油机运行要求标准

04

状态评估

定时分析，全面评估柴油机当前状态

一、启机过程两个阶段｛供气，发火｝

Two stages in the starting process

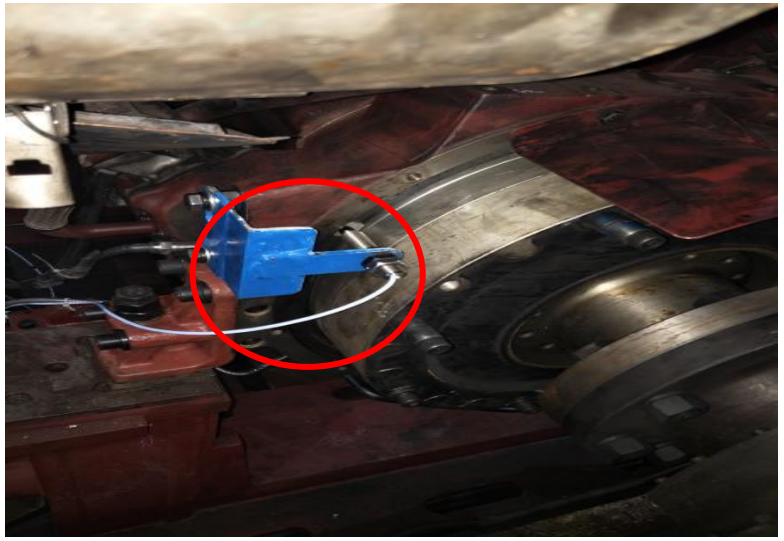
｛gas supply and ignition｝

信号采用：键相信号图，升速图（右上），周期耗时图（右中），瞬时转速图，缸盖振动图，做功分析（右下）等等。

The signal adopts: Key phasor signal diagram, speed up diagram (upper right), cycle time diagram (middle right), instantaneous speed diagram, cylinder head vibration diagram, work analysis (lower right), etc.

缸盖测点安装

Installation of measuring points



键相测点安装

Installation of measuring points

一、启机过程两个阶段｛供气，发火｝

Two stages in the starting process {gas supply and ignition}

特征采用：振动烈度，做功能力，启机位置，两周期时长，两周期数量，周期分割点，首个发火缸等等特征。

方式：自动产生评估报告

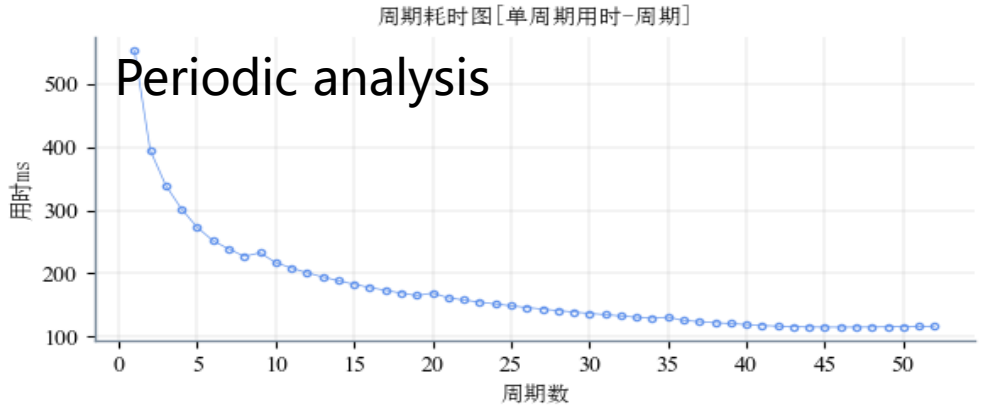
目的：全面评估柴油机启机过程

Features: vibration intensity, work capacity, starting position, duration of two cycles, number of two cycles, cycle division point, first firing cylinder, etc.

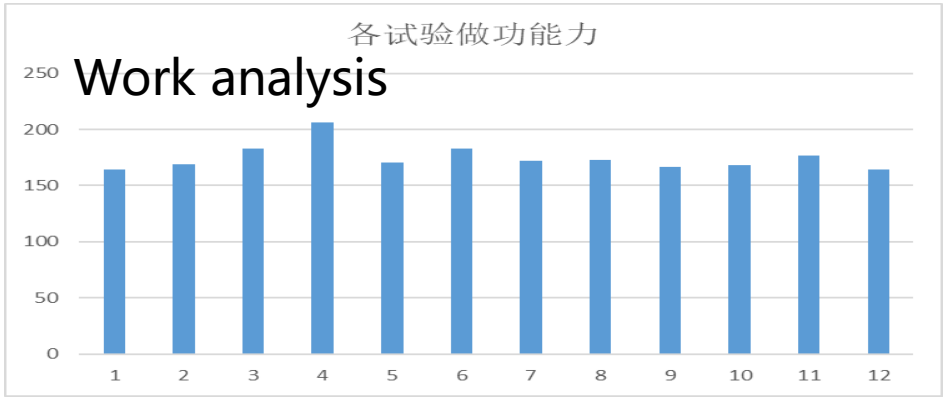
Method: automatically generate evaluation report

Objective: to comprehensively evaluate the starting process of diesel engine

速度分析图



周期分析图



做功分析图

二、稳定过程 Stabilization process

信号采用：

键相信号图，稳定转速图，缸盖振动图（右上），瞬时转速图（右中），箱体振动图，发电机振动图，传动箱振动图，以及上述各振动计算频谱图（右下）等等

The signal adopts:

Key phasor signal diagram, stable speed diagram, cylinder head vibration diagram (upper right), instantaneous speed diagram (middle right), box vibration diagram, generator vibration diagram, transmission box vibration diagram, as well as the above vibration calculation spectrum diagram (lower right), etc

箱体测点安装

Installation of measuring points

传动箱测点安装

Installation of measuring points

二、稳定过程 Stabilization process

特征采用：振动位置分析，振动烈度分析，振动峭歪度分析，关键位置振动烈度比分析，关键频率分析，关键频率能量比分析，整周期能量波动指标分析，全周期能量分布分析等等。

方式：自动产生评估报告

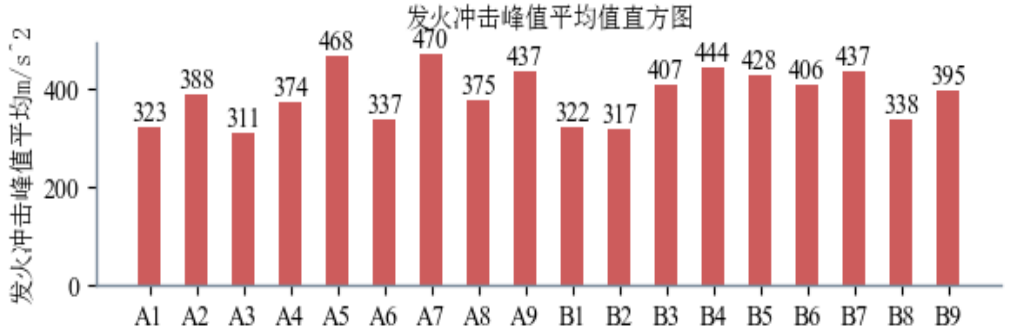
目的：全面评估柴油机长期运行过程状态

Features: : kurtosis ratio, vibration frequency analysis, vibration intensity analysis, full period analysis, key positio analysis, vibration intensity analysis, etc.

Method: automatically generate evaluation report

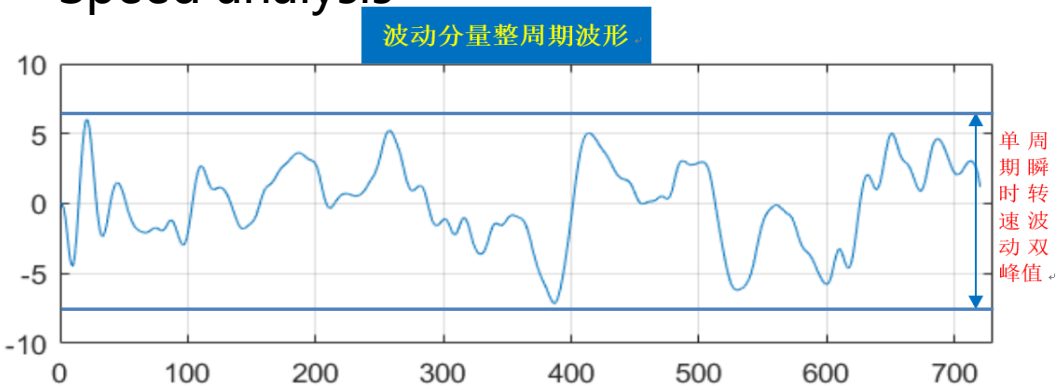
Objective: to comprehensively evaluate the long-term operation state of diesel engine

vibration analysis



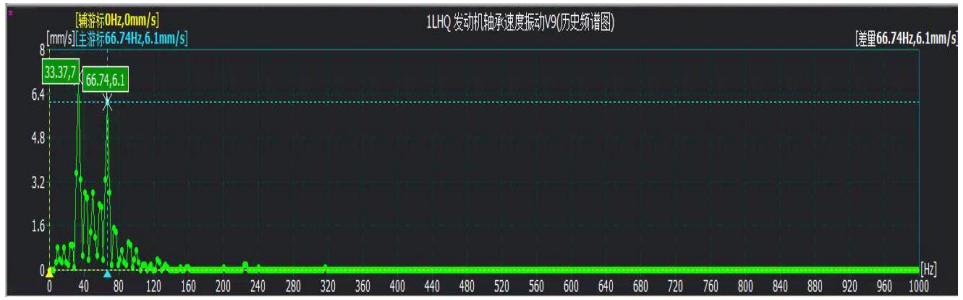
振动分析

Speed analysis



转速分析

Spectrum analysis



频谱分析

三、故障诊断预警 Fault diagnosis and warning

信号采用：稳定+启机所有信号

特征采用：硬阈值判断，软阈值判断等等。

方式：自动产生评估报告

目的：全面评估柴油机长期运行过程状态，是否存在故障趋势

Signal: stable + start all signals

Features: hard threshold judgment, soft threshold judgment and so on.

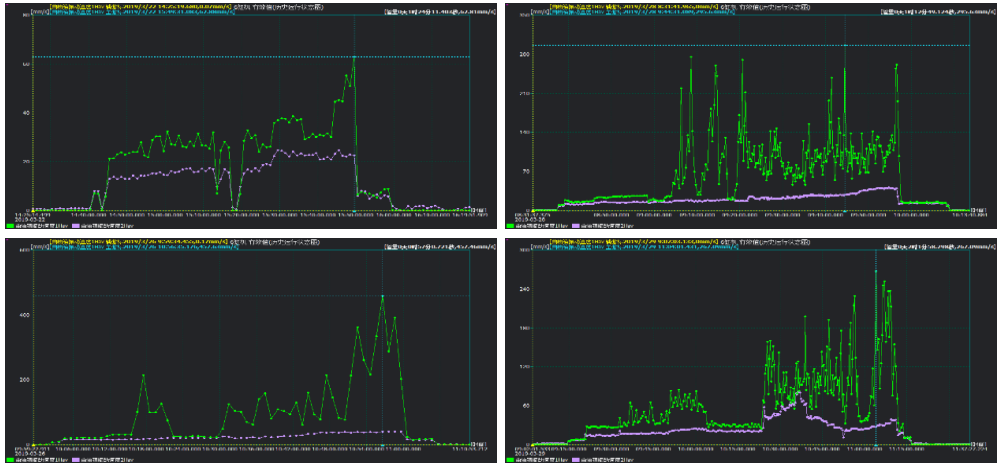
Method: automatically generate evaluation report

Objective: to comprehensively evaluate the status of diesel engine during long-term operation and whether there is fault trend

04 故障诊断预警+状态评估 Fault warning + evaluation report

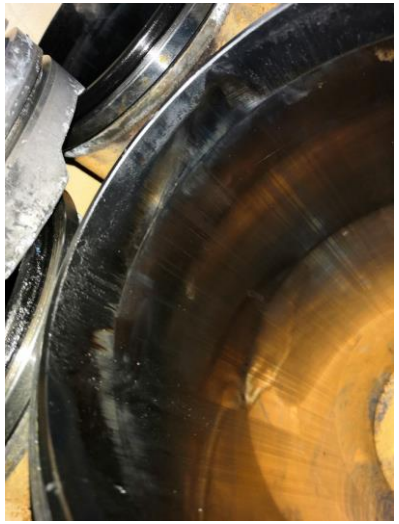
举例：拉缸故障案例 Example: cylinder pulling fault case

监测系统实时监测 Real time monitoring



Green fault

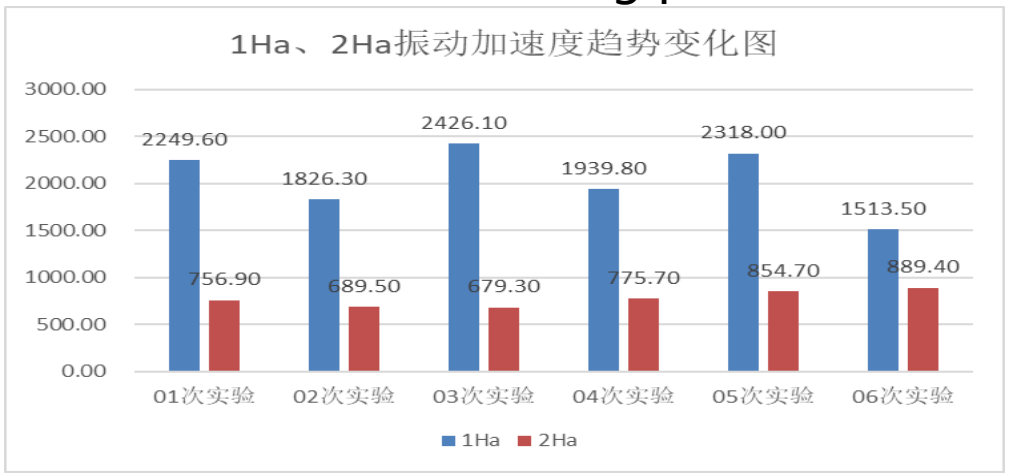
purple normal



某测点振动异常增大

The vibration of a measuring point increases abnormally

测点异常评估报告 Assessment report



某特征值监测

One eigenvalue monitoring

故障现场图片

Picture of fault site

04 故障诊断预警+状态评估 Fault warning + evaluation report

举例：失火故障案例

监测系统实时监测 Real time monitoring

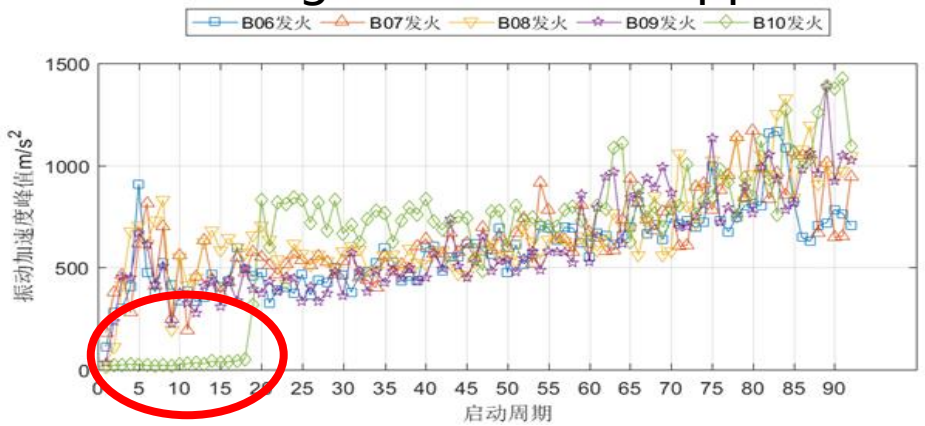
正常 Normal

失火 Fault

正常 Normal

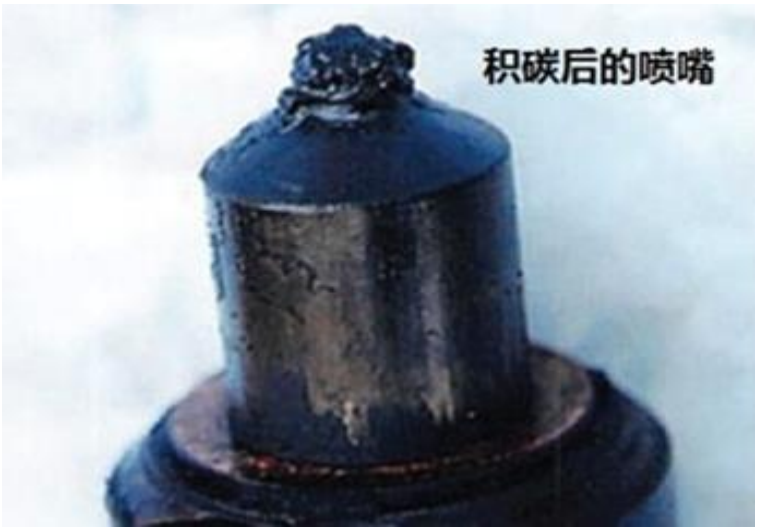
某测点发火角域振动消失
Fire angle vibration disappears

测点异常评估报告 Assessment report



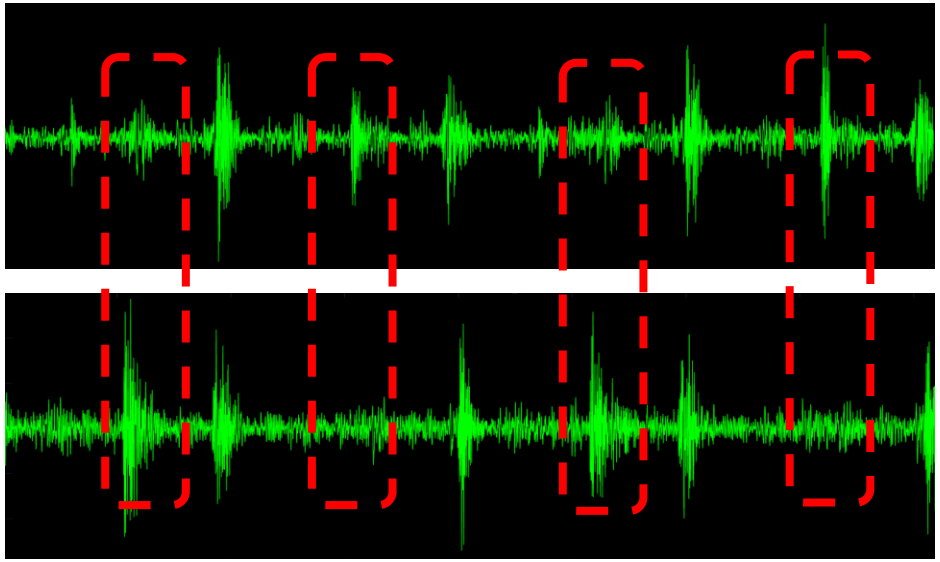
某特征值监测
One eigenvalue monitoring

故障现场图片
Picture of fault site



举例：气门间隙故障案例

监测系统实时监测 Real time monitoring

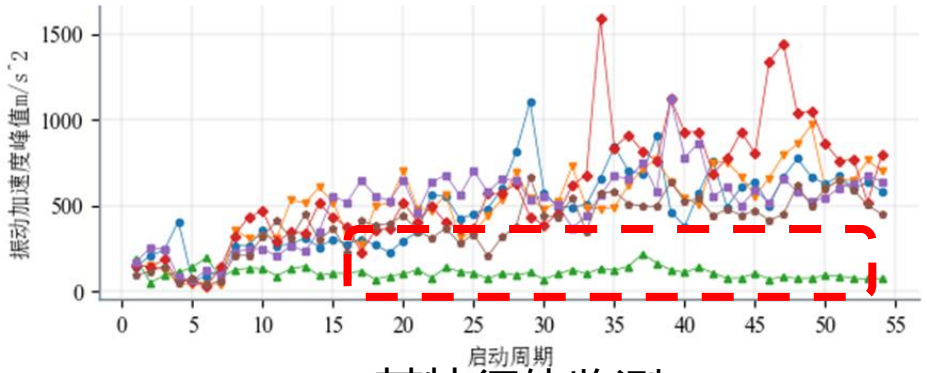


正常 Normal

故障 Fault

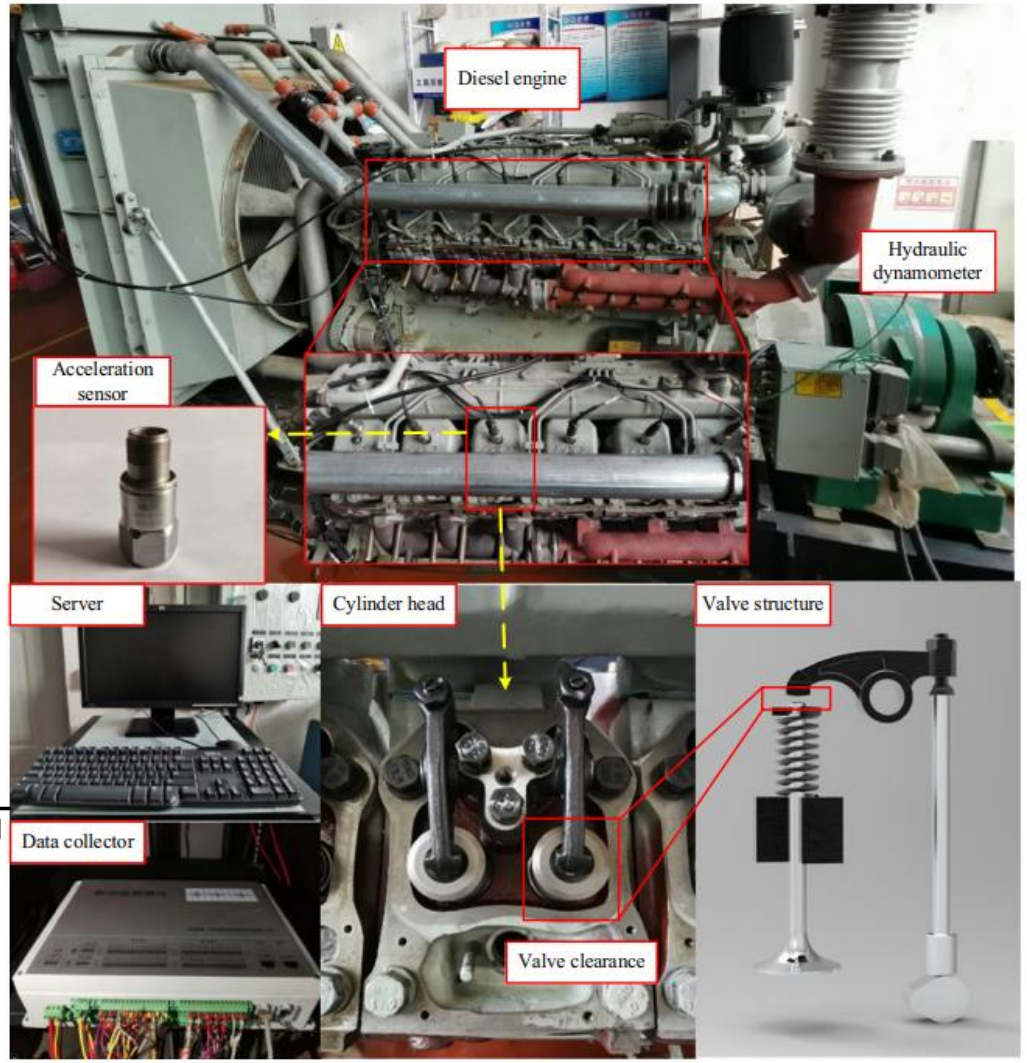
某测点气门角域振动烈度变化异常
Abnormal vibration intensity in valve angle domain

测点异常评估报告 Assessment report



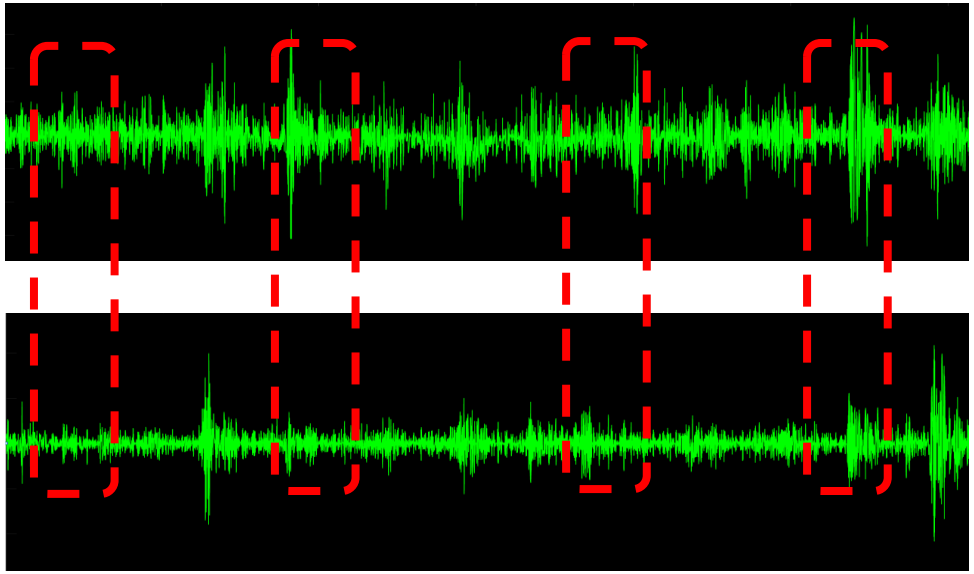
某特征值监测
One eigenvalue monitoring

故障现场图片
Picture of fault site



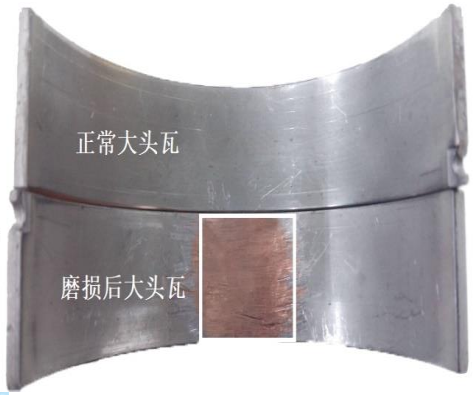
举例：轴瓦磨损故障案例

监测系统实时监测 Real time monitoring



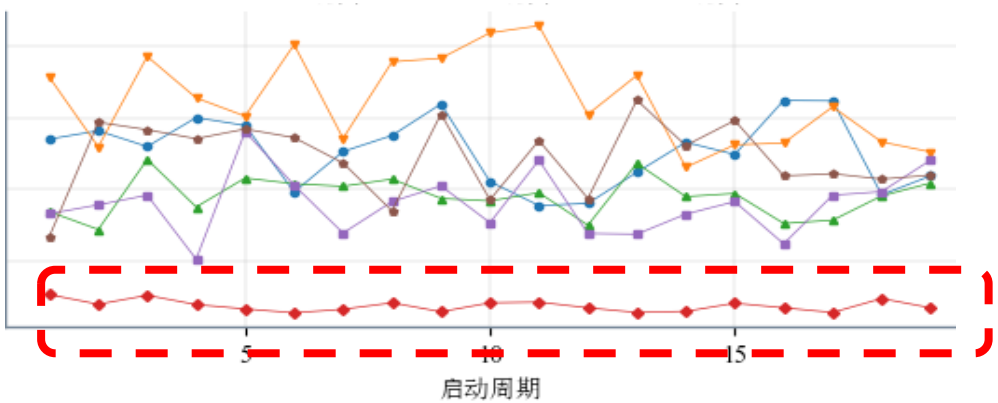
正常 Normal

故障 Fault



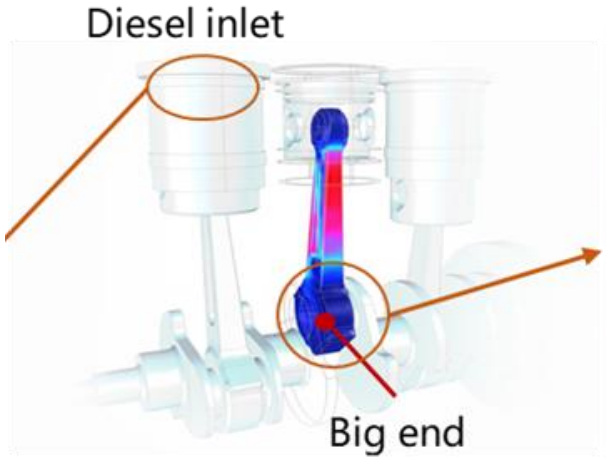
测点异常评估报告 Assessment report

某测点多处角域振动烈度变化异常



某特征值监测
One eigenvalue monitoring

故障现场图片
Picture of fault site



04 故障诊断预警+状态评估 Fault warning + evaluation report

在柴油机故障机理、监测诊断方面获得了国家自然科学基金、内燃机可靠性国家重点实验室开放基金支持，研究成果发表SCI\EI论文30余篇，授权发明专利15项，含美国发明专利2项；获省部级特等奖1项。

[1] Nanyang Zhao, Jinjie Zhang, Zhiwei Mao, Zhinong Jiang. Variational time–frequency adaptive decomposition of machine multi-impact vibration signals, Mechanical Systems and Signal Processing, 2023, 189, 110084. （1区TOP）

[2] Zijia Wang, Zhiwei Mao, Jinjie Zhang, Zhinong Jiang, Guoqing Xiong. A temporal correlation micro-visco-elastohydrodynamic lubrication model and its applications on internal combustion engine, Tribology International, 2023, 178, 108101. （1区TOP）

[3] Nanyang Zhao, Jinjie Zhang, Wensheng Ma, Zhinong Jiang, Zhiwei Mao. Variational time-domain decomposition of reciprocating machine multi-impact vibration signals, Mechanical Systems and Signal Processing, 2022, 172, 108977. （1区TOP）

[4] Zijia Wang, Jinjie Zhang, Zhinong Jiang, Wei Xiong, Zhiwei Mao. A transient and time lag deformation alternating-coupling micro elastohydrodynamic lubrication model, International Journal of Mechanical Sciences, 2021, 210, 106744. （1区TOP）

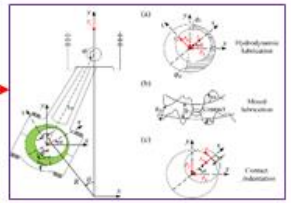
[5] Wang Zijia, Zhang Jinjie, Jiang Zhinong, Mao Zhiwei, Chang Kun, Wang Chenguang. Quantitative misalignment detection method for diesel engine based on the average of shaft vibration and shaft shape characteristics, Measurement, 2021, 181, 109527. （2区）

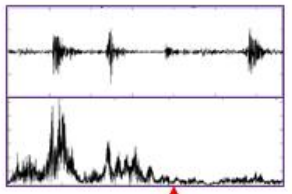
04 故障诊断预警+状态评估 Fault warning + evaluation report

申请国际发明专利2项，申请国家发明专利21项，共授权15项（红字）

2项
- 一种动载滑动轴承瞬态与时滞变形交替耦合作用的混合润滑模型建模方法
- 一种基于齿轮箱体振动响应的齿轮磨损均匀性辨识方法

故障机理研究





7项

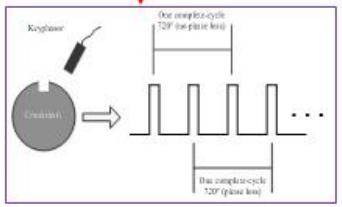
故障特征提取方法

- 一种尺度参数控制可调的信号包络线提取方法
- 一种基于EMD和Teager算子的变负荷活塞式发动机冲击特征提取方法
- 一种基于EMD的活塞式发动机冲击特征提取方法
- 一种基于多测点信息融合的柴油机振动冲击来源识别方法
- 一种多冲击振动信号时频分解方法
- 一种多冲击振动信号变分时域分解方法
- 一种基于能量算子k-梯度的往复机械振动信号冲击始点自适应提取方法

各类往复机械装备

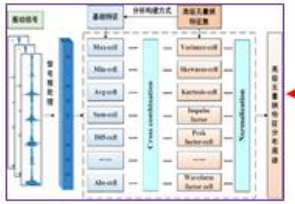
8项
- 一种基于缺齿齿盘轮齿脉冲的发动机监测信号整周期采集和瞬时转速计算方法
- 一种基于振动加速度信号的柴油机输出功率评估方法
- 一种基于往复机械活塞杆轴心轨迹包络与信息熵特征的负荷识别方法
- 一种基于相似性分析的往复压缩机信号整周期相位校准方法
- LOAD IDENTIFICATION METHOD FOR RECIPROCATING MACHINERY BASED ON INFORMATION ENTROPY AND ENVELOPE FEATURES OF AXIS TRAJECTORY OF PISTON ROD（美国）
- 活塞发动机曲轴停机相位在线监测方法
- 一种基于振动机理与深度学习技术的整周期无键相监测方法
- 一种往复压缩机信号的无键相角域周期分割方法

监测信号预处理方法



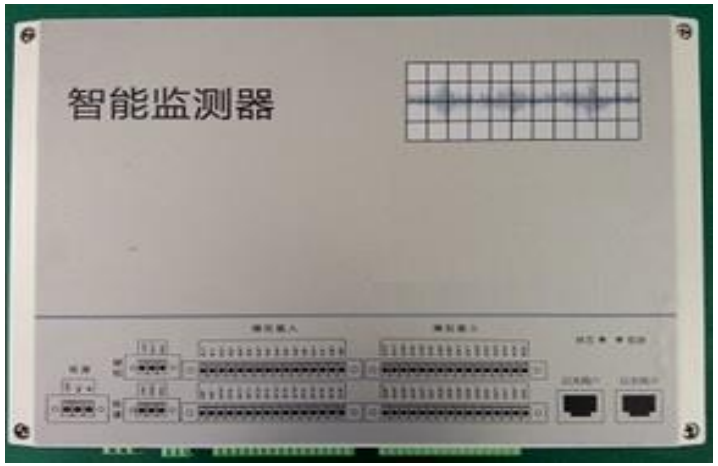
6项

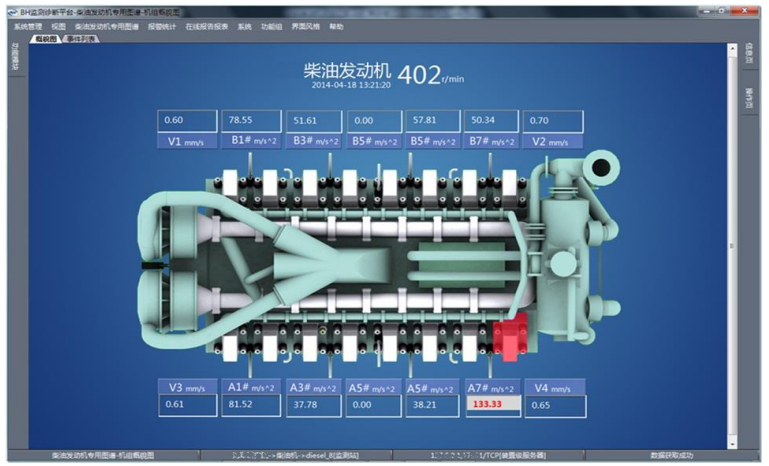
故障诊断模型构建

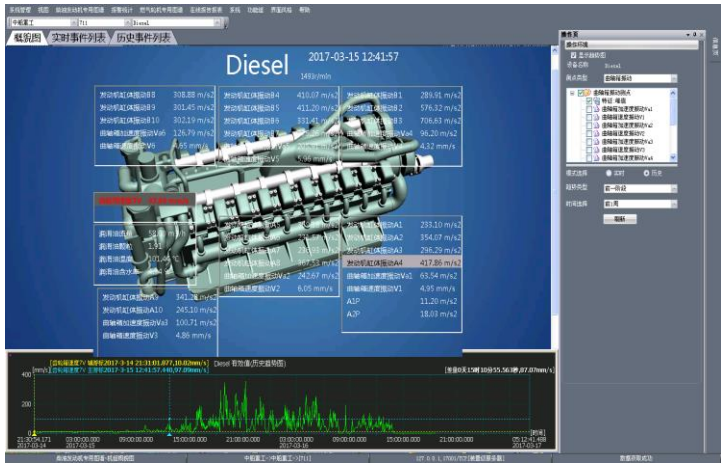


- 一种基于无故障振动信号的往复机械异常检测方法
- 一种基于无键相整周期信号的往复机械故障诊断方法
- 一种基于模拟示功图的往复压缩机连杆大、小头瓦故障诊断方法
- 一种基于无量纲指数的往复压缩机故障监测诊断方法
- FAULT DIAGNOSIS METHOD OF RECIPROCATING MACHINERY BASED ON KEYPHASOR-FREE COMPLETE-CYCLE SIGNAL（美国）
- 基于结合传统诊断与机器学习方法且针对往复机械气门间隙异常故障的诊断模型构建方法

工程应用方面：研发监测诊断系统已在JG多个型号柴油机可靠性试验、国内柴油机厂试车台与核电应急柴油机上得到工程应用，包括河南柴油机重工有限责任公司、潍柴集团、上海沪东重机、大亚湾核电站、秦山核电站等，成功预警诊断了气门组件磨损、齿轮断裂、联轴器断裂、失火等典型故障。







Thanks!

北京化工大学 张进杰 副教授

Speaker：Jinjie Zhang

Email：zhangjinjie@buct.edu.cn

电话：13501124380