柴油机故障检测研究的实践

Practice of diesel engine fault detection research

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故障诊断的概述
An overview of fault diagnosis

- 故障：系统中部分元器件功能失效而导致系统功能恶化的事件
  Fault： The event that the function of some components in the system fails, resulting in the deterioration of the system function;
- 故障诊断：故障诊断是对系统运行状态和异常情况作出判断，并根据诊断作出判断，为系统故障恢复提供依据。
  Fault diagnosis： Fault diagnosis is to judge the operation status and abnormal conditions of the system, and make judgment based on the diagnosis to provide basis for system fault recovery ;
- 故障诊断主要任务有：故障检测、故障类型判断、故障定位及故障恢复等。
  The main tasks of fault diagnosis are： Fault detection、 Fault type judgment、 Fault location and recovery etc.

故障检测实现精准识别系统状态，是故障诊断基础。
Fault diagnosis realizes accurate identification of system status, which is the basis of fault diagnosis.

经验检测
(Experience test)

智能检测
(Intelligent detection)

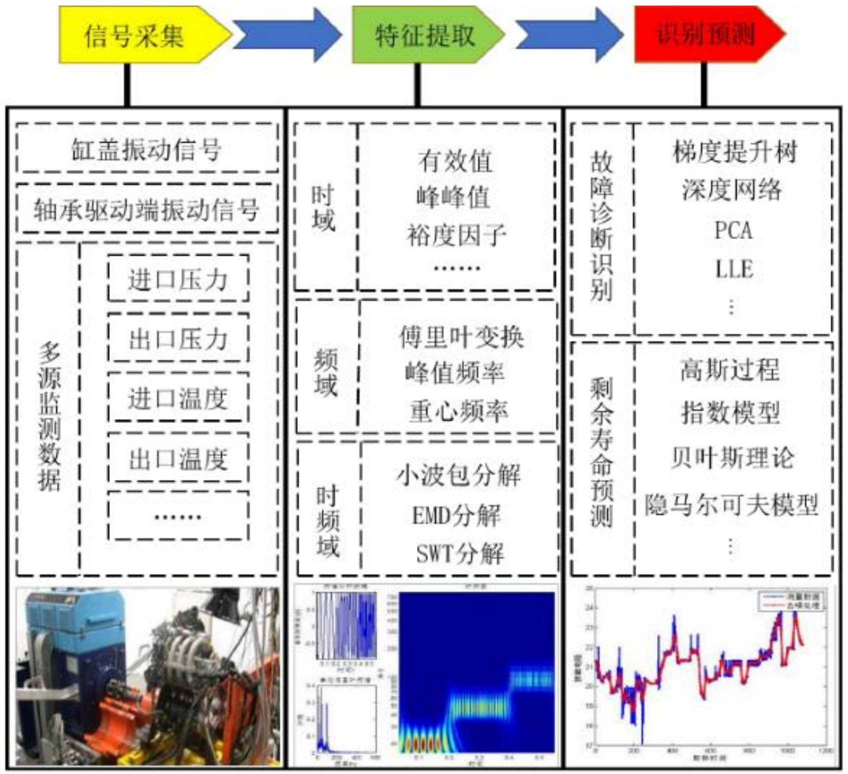
离线诊断：主要在非运行时**加以检测**，从而实现故障的诊断。
Offline diagnosis: It is mainly detected when it is not running, so as to realize fault diagnosis.

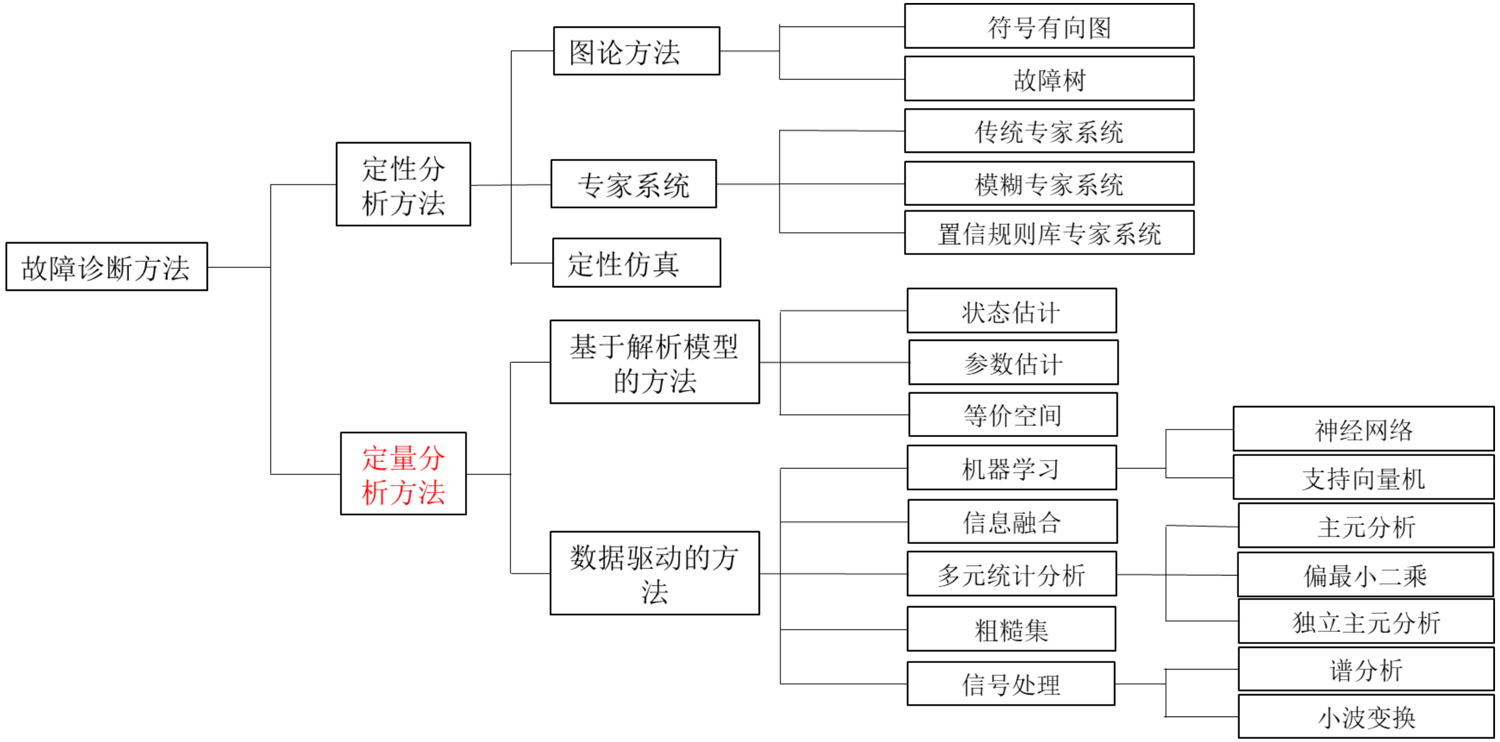
在线诊断：主要是指系统运行时自动**自诊断**，主要以故障代码的方式传输（OBD）。
Online diagnosis: It mainly refers to automatic self-diagnosis when the system is running, mainly by means of fault code transmission (OBD).

在线诊断的关键
The key to online diagnosis

通过**定量**的判断，精准分析系统状态。

Through quantitative judgment, accurate analysis of system status.





系统状态由特征量表征，关键：选择什么特征量？特征量是定量获得？

The state of the system is represented by the characteristic quantity.

Key： What characteristic quantity is chosen? is the characteristic quantity obtained quantitatively?

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实践一　基于轨压的喷油量识别

Practice one Identification of fuel injection quantity based on rail pressure

问题的提出
Questions raised

- 对于柴油机来说，喷油器喷油量直接决定了发动机输出扭矩；

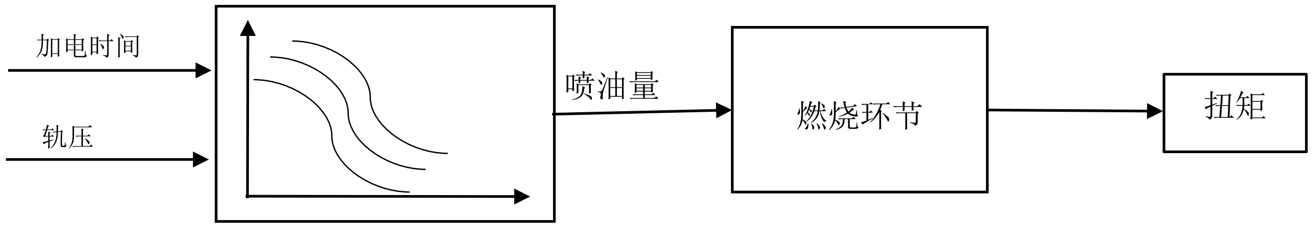
  For a diesel engine, the amount of fuel injected directly determines the engine output torque ；

- 若喷油量发生变动，则发动机扭矩也会随之改变；

  If the amount of fuel injection changes, then the engine torque will also change ；

- 现阶段对于喷油量不进行闭环识别，是通过开环的方式直接由加电时间和轨压决定喷油量，但是这种控制需要以保证喷油器的流通能力在整个使用寿命中不发生变化为前提；

  At this stage, there is no closed-loop identification for the amount of fuel injection, which is directly determined by the power-on time and rail pressure by the way of open-loop, however, this control needs to ensure that the flow capacity of the injector throughout the life of the premise does not change ；



（a）新喷油器　（b）积碳喷油器 1　（c）积碳喷油器 2

- 实际中喷油器流通能力会发生变化，如磨损、积碳；因此对喷油器的流通能力进行闭环诊断非常重要（法规要求）

  In practice, the flow capacity of the injector will change, such as wear, carbon deposition ；（ Statutory requirements ）

当前方案
Current scenario

- 基于瞬态转速：转动惯量由于传动系统的加入会出现波动：

  Based on transient speed: the moment of inertia fluctuates due to the addition of the transmission system ：

$$\omega = {T_f}/{J_\omega}$$

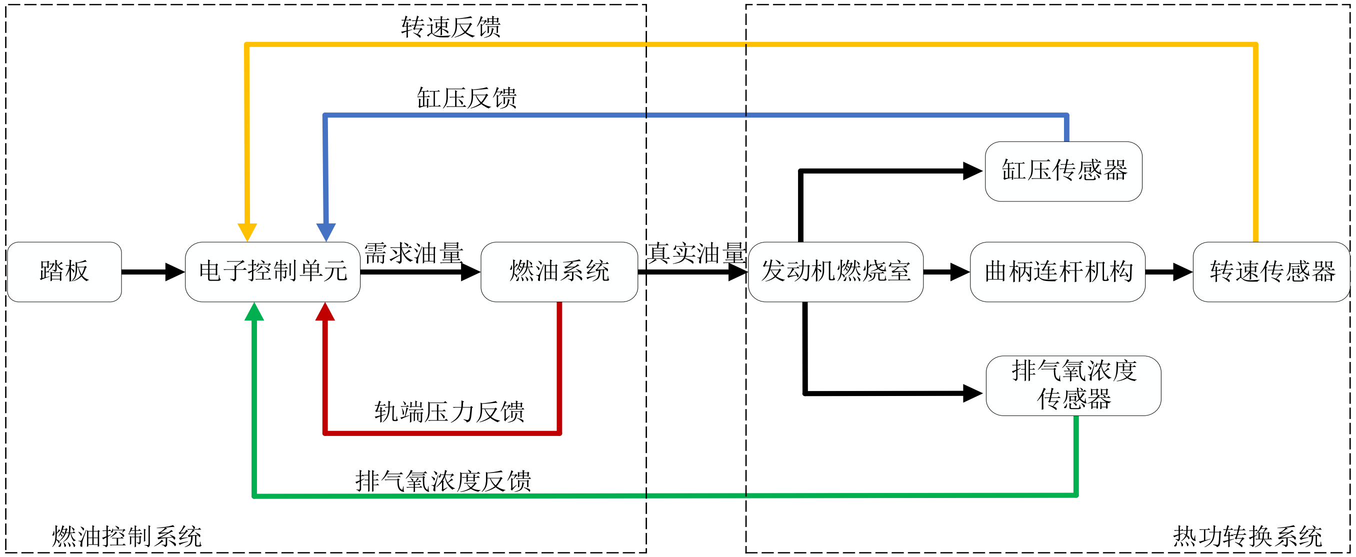
- 基于排气氧浓度：受限于进气流量的精确识别和氧浓度传感器的高频响应；

  Based on exhaust oxygen concentration: limited by the accurate identification of intake flow and oxygen concentration sensor high-frequency response ；

$$q_m = \frac{m_{ar}}{\dfrac{\left(1+\dfrac{b+2c}{4a+b-2c}\cdot\varphi_m\right)\cdot\dfrac{M_{Air}}{M_{O_2}}\cdot\varphi_{M,O_2,Air}}{\varphi_{V,O_2,Air}-\varphi_{V,O_2,Exh}}\cdot l_0}$$

- 基于缸压：必须要使用瞬时缸压传感器，但是发动机上并无此传感器，因此无法进行测量；

  Based on cylinder pressure: an instantaneous cylinder pressure sensor must be used, but it is not available on the engine and therefore can not be measured



目前方法通过燃油变动引起燃烧变动，根据燃烧变动之后的响应进行动态偏差识别。

At present, the method can identify the dynamic deviation according to the response after the change of combustion caused by the change of fuel oil.

基于轨压检测的原理
Based on the principle of rail pressure detection

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由燃油流速变化引起的轨端压力变化
The change of rail end pressure caused by the change of fuel flow rate

喷射过程中燃油在高压油管内的流速为：

During the injection process, the flow rate of fuel in the high-pressure fuel pipe is： $v=\frac{n\mu A_0}{A}\sqrt{\frac{2(P_A-P_r)}{\rho}}$

由燃油流速变化引起的轨端压力变化满足：

The rail end pressure change caused by the change of fuel flow velocity is satisfied： $\Delta P=P_B-P_B'=\frac{BQ}{V}=\int_0^t\frac{B}{V}v_A A dt=\int_0^t\frac{Bn\mu A_0}{V}\sqrt{\frac{2(P_A-P_r)}{\rho}}dt$

由压力波引起的轨端压力变化
The change of rail end pressure caused by pressure wave

在弹性管道中水击波速公式为：

The formula for the velocity of water hammer in an elastic pipe is：

$$u_c=\frac{\sqrt{B/\rho}}{\sqrt{1+B\,D/E\,\delta}}$$

考虑到水击压力波的周期性变化，以及由于水机压力波传播到共轨端的时间延迟，整理得到水击压力波对轨端压力影响的分段周期函数：

Considering the periodic change of water hammer pressure wave and the time delay of water turbine pressure wave propagating to common rail end, the piecewise periodic function of water hammer pressure wave effect on rail end pressure is obtained：

$$dP_2=\begin{cases}0 & 0\le t\le L/c\\ \Delta H(t) & L/c<t\le 2L/c,\ 4L/c<t\le 6L/c,\ 8L/c\le t\le 10L/c,\dots\\ -\Delta H(t) & 2L/c<t\le 4L/c,\ 6L/c<t\le 8L/c,\ 10L/c<t\le 12L/c,\dots\end{cases}$$

- 喷油流速会显著影响轨压变动；
  The injection velocity will affect the rail pressure significantly；
- 因为压力波的叠加，使得轨端压力变化的响应时间会发生滞后；
  Because of the superposition of the pressure waves, the response time of the pressure change at the rail end will be delayed；

$$\Delta P_{总}=\Delta P+\Delta P'$$

定义k为ΔP对t的导数：

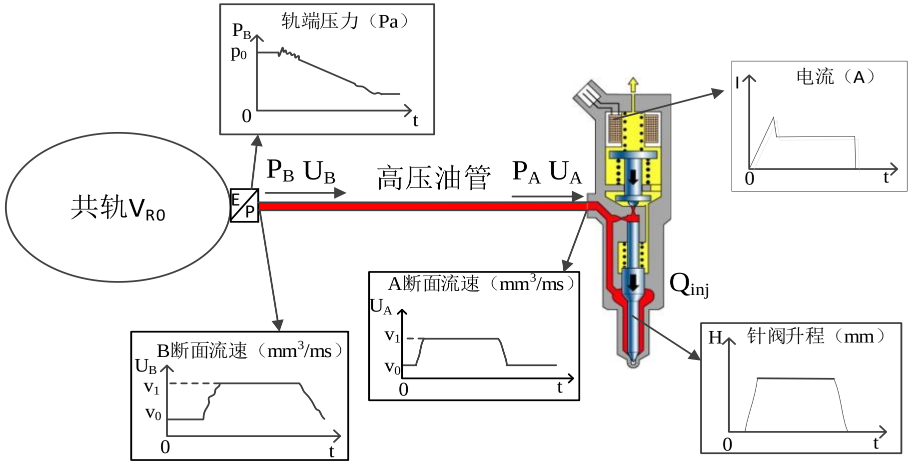
Define K as the derivative of ΔP to t：

$$K=\frac{dP}{dt}=\frac{Bn\mu A_0}{V}\sqrt{\frac{2(P_A-P_r)}{\rho}}$$

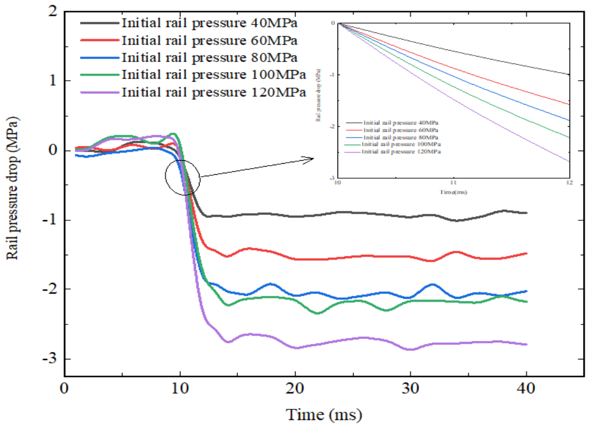
基于上述分析，利用轨压降与加电时间之间的函数关系对发动机运行时的喷油速率进行识别，喷油速率为：

Based on the above analysis, the fuel injection rate is identified by using the function relationship between rail pressure drop and power-on time：

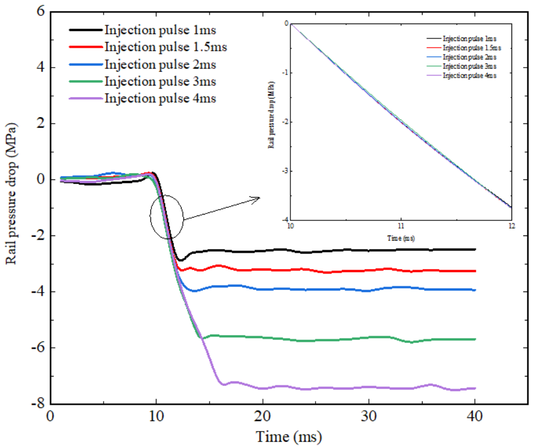
$$Q_{inj}=\int_0^t n\,v_0A_0dt=\int_0^t\frac{KV}{B}dt$$



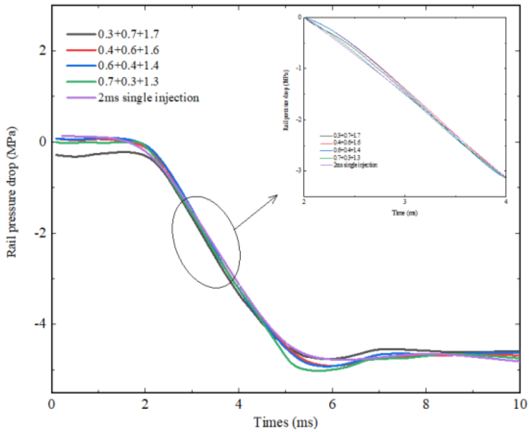
实验分析
Experimental Analysis



不同初始轨压
Under different initial rail pressure conditions

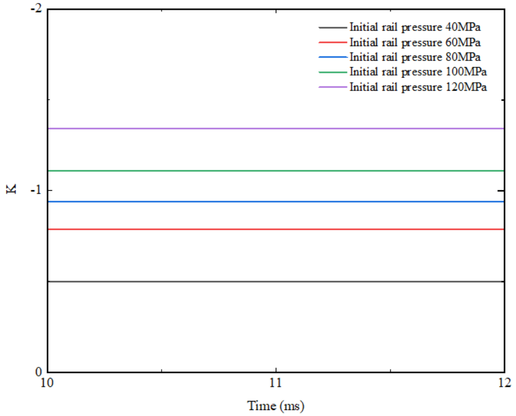


不同喷油脉宽
Under different injection pulse width condition

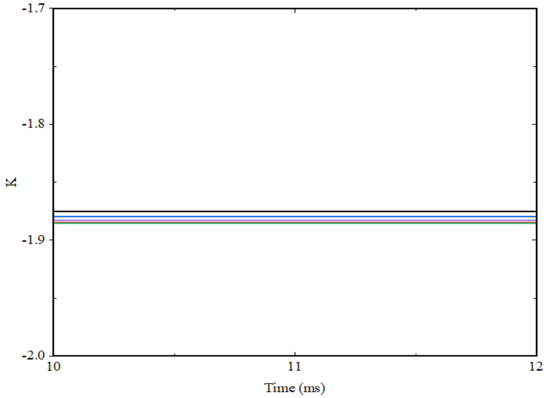


不同喷射方式
Under single injection and multiple injection with different pulse width combinations

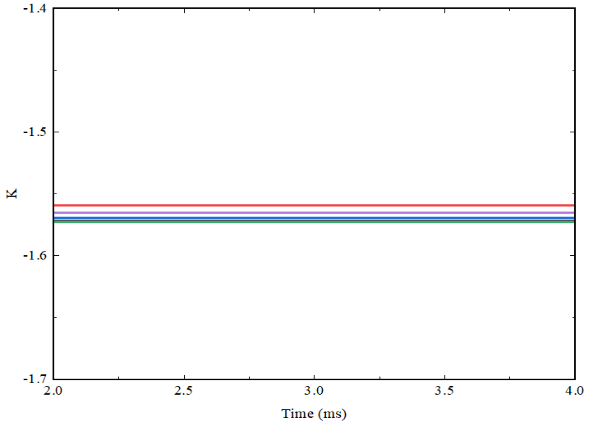
- ➢ 随着初始压力和喷油脉宽的增加，轨压降增加；
  The rail pressure drop increases with the increase of initial pressure and injection pulse width；
- ➢ 轨压降不受喷射模式的影响。
- ➢ The rail pressure drop is not affected by the injection mode .



不同初始轨压
Under different initial rail pressure conditions



不同喷油脉宽
Under different injection pulse width condition



不同喷射方式
Under single injection and multiple injection with different pulse width combinations

K值与初始压力有关。
The K value is related to the initial pressure.

结论
Conclusion

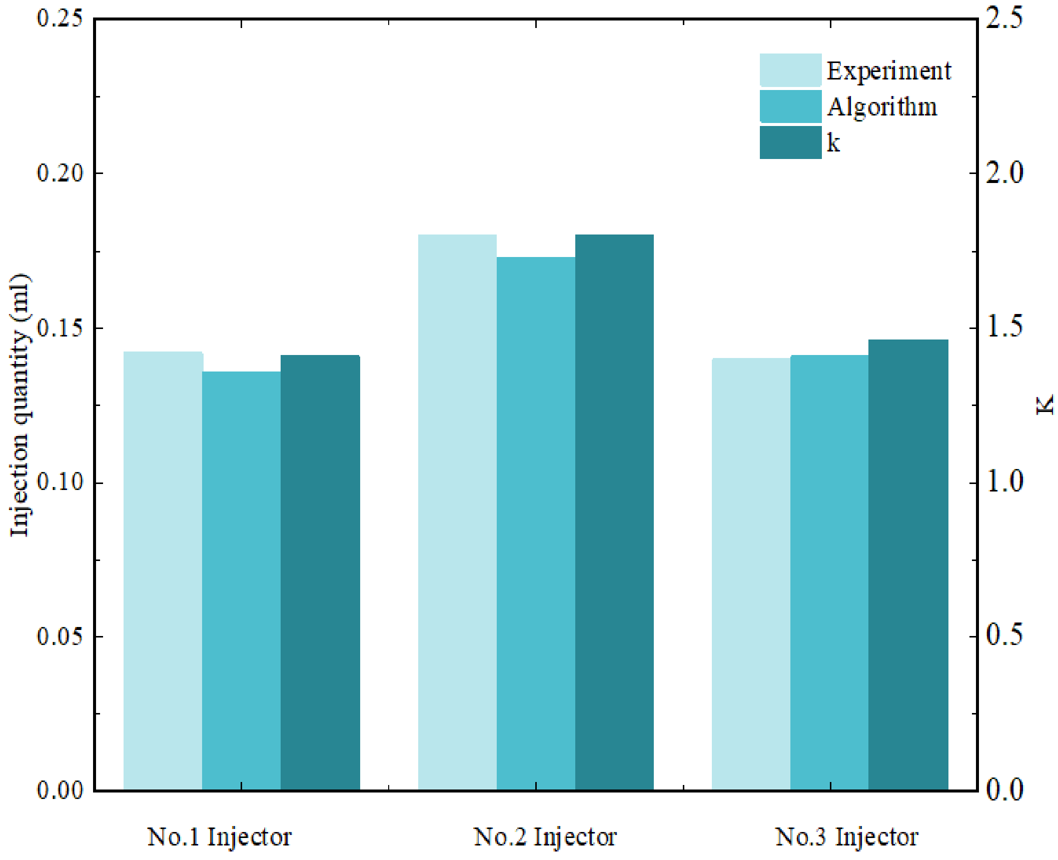
$$Q_{inj} = \int_0^t n\, v_0 A_0 dt = \int_0^t \frac{KV}{B} dt$$

基于K值，提出了一种合适的喷油量识别算法。实验结果表明，初始压力不变，当喷油量变化时，该算法可以识别异常喷射行为并估计喷油量。

Based on k-value, a suitable algorithm for fuel injection quantity identification is proposed. The experimental results show that the algorithm can identify abnormal injection behavior and estimate injection volume when the initial pressure is constant and the injection volume is changed.

在喷射脉宽较长且油泵泵油速率较低时，该方法更准确地工作。

When the injection pulse width is longer and the pump speed is lower, the method works more accurately.



算法与实验喷油量比较
Comparison of injection quantity between experiment and algorithm

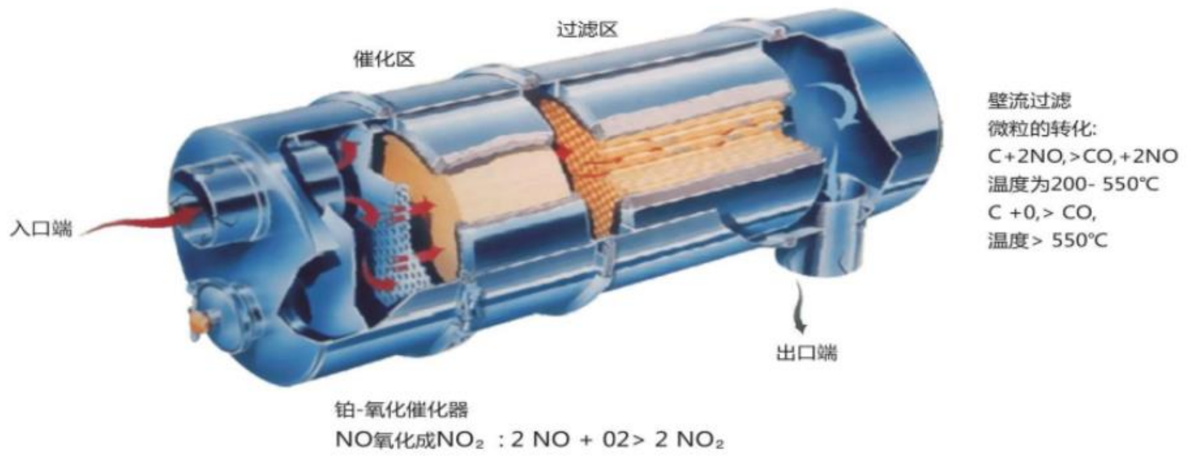
Ma X , Lei Y , Qiu T , et al. Investigation of fuel injection rate identification algorithm based on rail pressure fluctuation characteristics induced by injection:[J]. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2022, 236(6):1101-1114.

实践二　基于DPF时间常数的积碳量识别

Practice two Identification of soot loading based on DPF time constant

问题的提出
Questions raised

- 柴油机热效率高、可靠性高，广泛应用于重型车辆、船舶、机车和发电机；
  Diesel engine is widely used in heavy-duty vehicles, ships, locomotives and generators for its high thermal efficiency and high reliability；
- 柴油机的颗粒物排放高对人类健康和环境都有不利影响；
  High particulate matter emissions from diesel engines have adverse effects on human health and the environment ；
- 柴油机主要采用微粒捕集器（Diesel Particulate Filter，DPF）来控制排气中的颗粒物。
  The diesel engine mainly uses the Diesel Particulate Filter (DPF) to control the particulate matter in the exhaust .



过滤壁孔隙严重“堵塞”
Serious "Clogging" of pore in filter wall

↓

DPF上下游压降过高，柴油机性能恶化
DPF upstream and downstream pressure drop is too high, diesel engine performance deterioration

↓

再生
Regeneration

精准识别出DPF内积碳量是再生控制的关键。
Accurate identification of soot loading in DPF is the key to regeneration control.

当前方案
Current scenario

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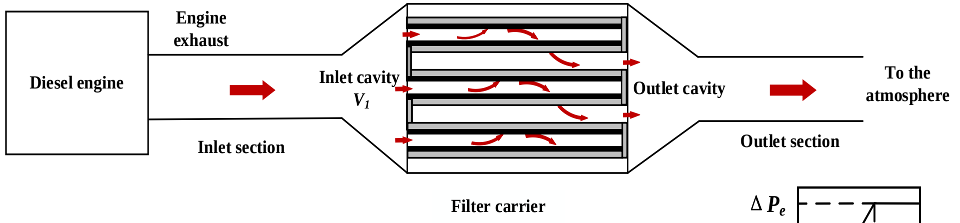
	在线 Online			离线 Offline
方法 Method	压差法 Pressure drop method	模型法 Model method	传感器直接测量 Sensor direct measurement method	直接称重 Weigh directly
基本原理 Basic principle	依据DPF两端压差的变化对积碳量进行识别。 The soot loading is identified by the pressure drop of the DPF.	依据内燃机内燃烧后得到的碳量减去后处理的再生量对积碳量进行识别。 The soot loading is identified according to the soot loading obtained after internal combustion minus the regeneration.	基于电学原理的颗粒物传感器对积碳量进行识别。 The soot loading is identified by a soot particle sensor based on the electrical principle.	天平称重 The scales are weighed
积碳量识别下限 The lower limit of soot loading recognition	2g/L	2-3g/L	3g/L	精确测量 Accurate measurement

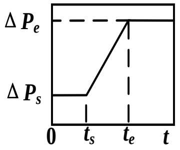
小碳量的在线识别？

Online identification of low soot loading?

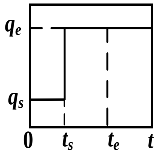
基于动态过程的识别方法
Identification method based on dynamic process

- DPF是一个腔和流阻组合结构，可以等效为电阻和电容并联电路。
  DPF is a combination of cavity and flow resistor, which can be equivalent to resistor and capacitor parallel circuit .
- 发动机动态工况时，DPF的进出口流动为暂态过程，该过程会可以通过时间常数t_c来评价。
  When the engine is in dynamic condition, the flow of DPF is a transient process, which can be evaluated by time constant t_c.

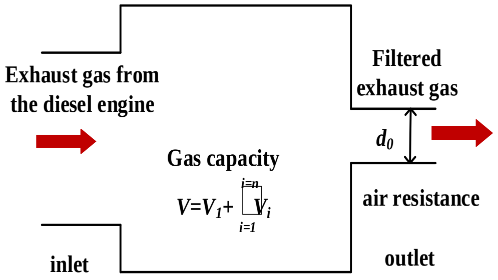


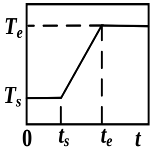


Change of pressure drop of air resistance with time

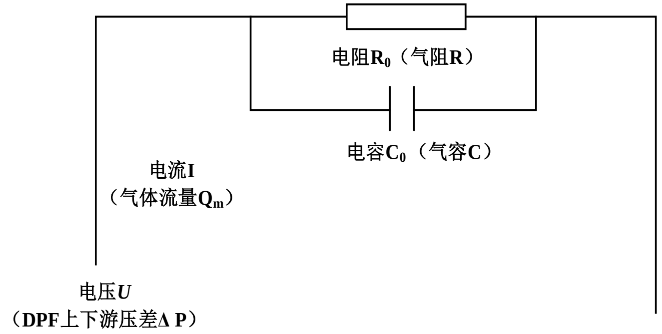


Change of inlet flow with time





Change of air resistance outlet temperature with time



气阻R可由如下表达式求出：
The gas resistance R can be derived from the following expression:

$$R=\frac{dP}{dQ}\frac{2\mu(d+\delta_w)^2}{\pi D^2 L}\left[\frac{\delta_w}{k_w d}+\frac{1}{2k_s}\ln\left(\frac{d\sqrt{nL\rho_s}}{\sqrt{nL\rho_s d^2-m_s}}\right)+\frac{4FL^2}{3d^4}\right]$$

假设DPF流动过程为绝热过程，气容C表达式如下：
Assuming that the DPF flow process is adiabatic, the gas capacity C expression is as follows:

$$C=\frac{dm}{dP}=\frac{V}{kRT}$$

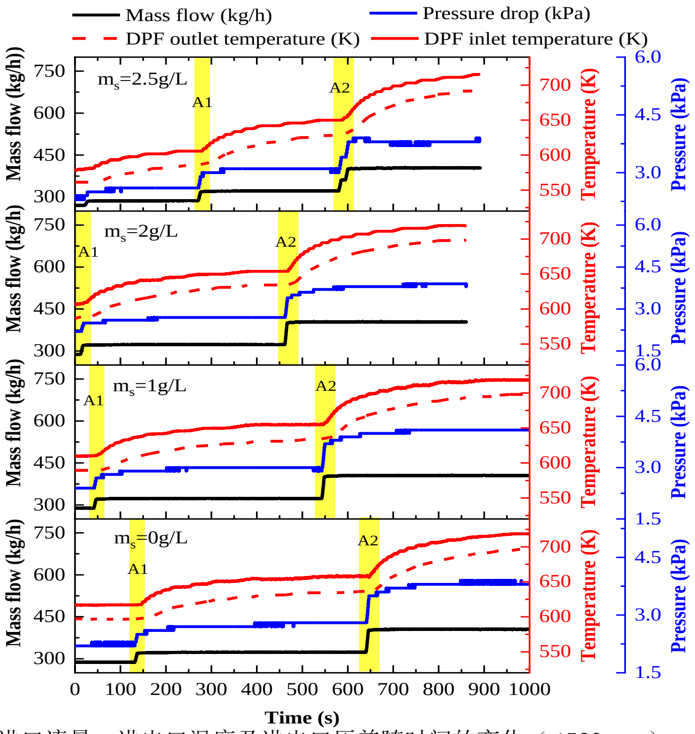
以上分析DPF的时间常数t_c：
The time constants for DPF are analyzed above t_c：

$$t_c=CR=\frac{\beta_1+\beta_2\ln\left(\frac{\beta_3}{\sqrt{\beta_4-m_s}}\right)}{T}$$

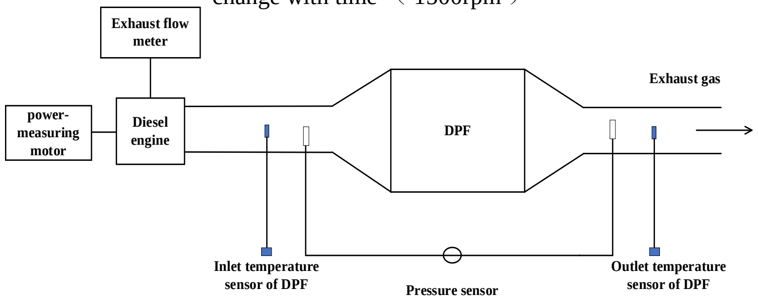
其中β_1-β_4为常量，$\beta_1=\frac{2\mu(d+\delta_w)^2V}{\pi D^2 LkR}\left(\frac{\delta_w}{k_w d}+\frac{4FL^2}{3d^4}\right)$, $\beta_2=\frac{\mu(d+\delta_w)^2V}{k_s\pi D^2 LkR}$, $\beta_3=d\sqrt{nL\rho_s}$, $\beta_4=nL\rho_s d^2$。

1. t_c与积碳量m_s及来流温度T相关，即$t_c=f(T,m_s)$，且$t_c\propto\ln\left(\frac{\beta_3}{\sqrt{\beta_4-m_s}}\right)\propto\frac{1}{T}$;
   t_c is related to the amount of carbon deposition m_s and the inflow temperature T, that is $t_c=f(T,m_s)$, and $t_c\propto\ln\left(\frac{\beta_3}{\sqrt{\beta_4-m_s}}\right)\propto\frac{1}{T}$;
2. 当m_s不变时，来流温度T升高，则t_c减小；
   When m_s is constant, the inlet temperature T increases, then t_c decreases;
3. 当来流温度T不变时，积碳量m_s增加，t_c增大。
   When the inlet temperature T is constant, the amount of carbon deposit m_s increases and t_c increases.

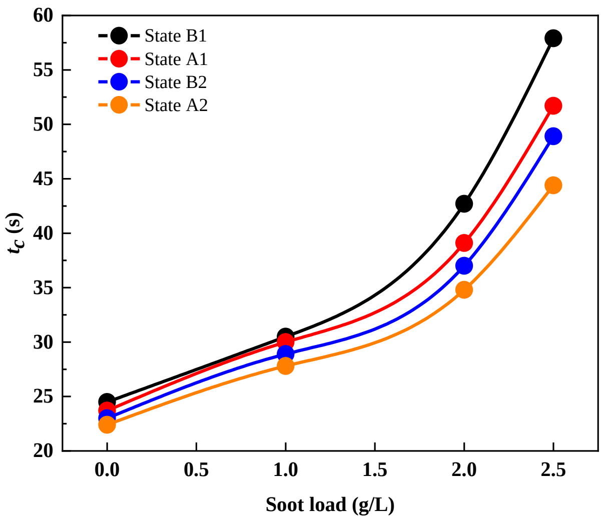
实验分析与结论
Experimental analysis and conclusion



DPF进口流量、进出口温度及进出口压差随时间的变化（ 1500rpm ）
DPF inlet flow rate, inlet and outlet temperature and inlet and outlet pressure difference change with time （ 1500rpm ）

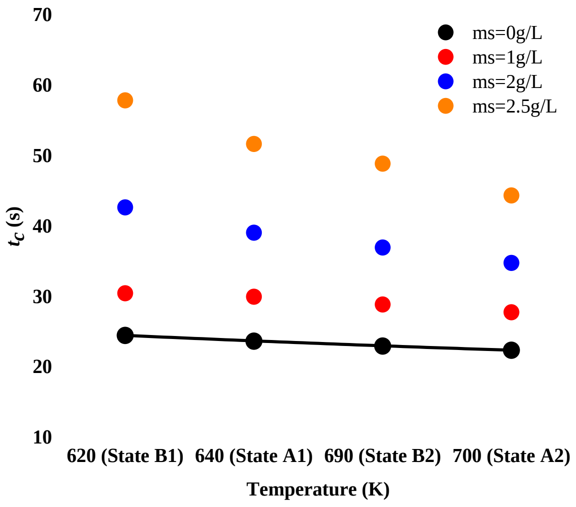


DPF时间常数可以通过温度延时表征
DPF time constant can be characterized by temperature delay.

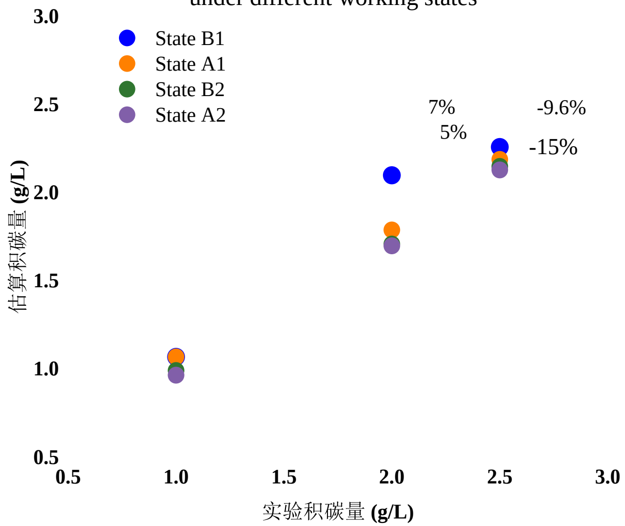


不同工况稳定时间t_c随积碳量的变化
The variation of the time constant (t_c) with incoming temperature (T) for different soot loading (m_s)

$$m_s = \beta_4 - \frac{{\beta_3}^2}{e^{\frac{t_c T - \beta_1}{\beta_2}}}$$



不同积碳量稳定时间t_c随温度T的变化
The time constant (t_c) changes with the soot loading (m_s) under different working states



算法验证
Algorithm validation

Qiu T , Ma X , Lei Y , et al. Study on estimation method of soot loading under dynamic working state (已投)

- 模型要选则合适的变量，如果没有直接传感器，则需要利用虚拟的信号进行诊断；

  Select appropriate variables for the model. If there is no direct sensor, it is necessary to use the virtual signal for diagnosis；

- 需要确定所检测对象与所选择的变量之间明确的表征关系。

  It is necessary to determine the clear characterization relationship between the tested object and the selected variable.

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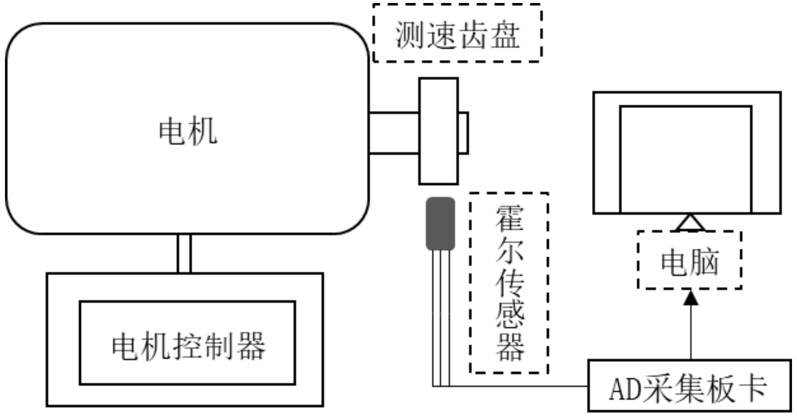
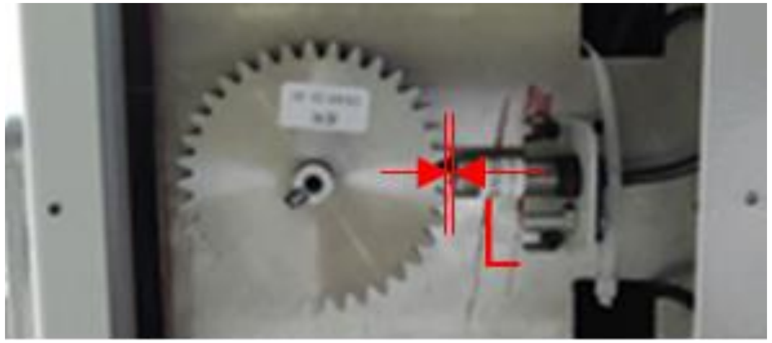
实践一　霍尔传感器间隙检测

Practice one Hall sensor gap detection

问题的提出
Questions raised

- 霍尔元件的灵敏度较低，其与齿轮要保持比较近的检测距离。
- The sensitivity of the Hall element is low, and it should keep a relatively close detection distance from the gear ;
- 齿盘、传感器松动的本质是传感器与齿盘之间的工作间隙变化引起的信号异常。
- The essence of loose tooth plate and sensor is the abnormal signal caused by the change of working clearance between sensor and tooth plate.





实验装置示意图
Schematic diagram of experimental device

改变传感器间隙大小，采集不同间隙的传感器信号，模拟因间隙变化引起的故障出现过程。
Change the gap size of the sensor, collect the sensor signals of different gaps, and simulate the process of failure caused by the gap change.

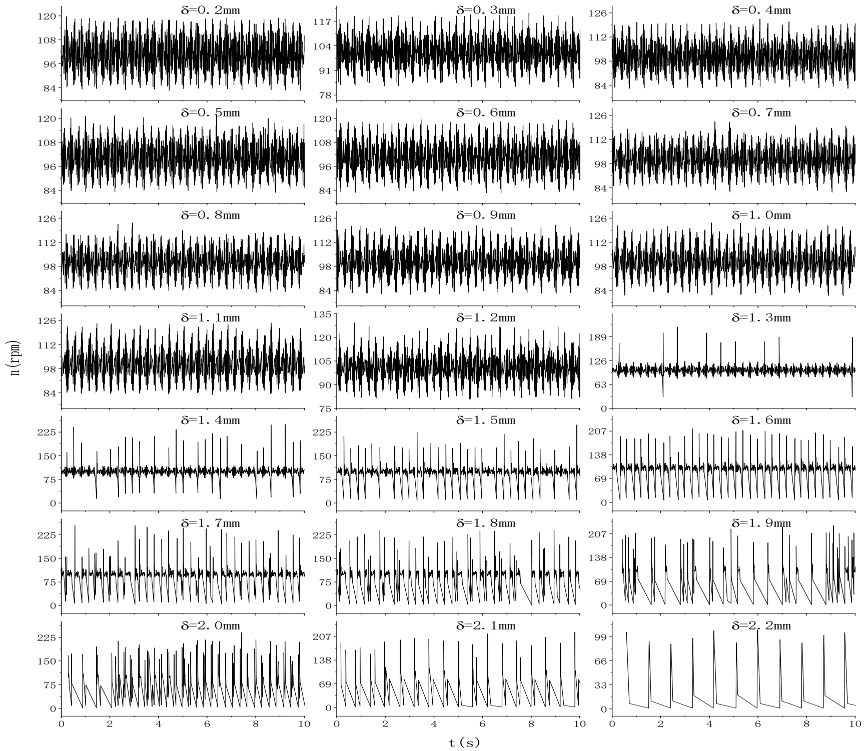
$$\Delta\Phi = \Phi_m^T - \Phi_m^B = \frac{F\mu_0 Sh}{\delta(\delta + h)}, \Delta E = E_{HT} - E_{HB} = \frac{R_H I F \mu_0 h}{D\delta(\delta + h)}$$

间隙δ影响磁阻大小，随着间隙增大磁阻也将增大，磁通量与霍尔电压将随之减少。
Gap δ affects the magnetic resistance. As the gap increases, the magnetic resistance will also increase, and the magnetic flux and Hall voltage will decrease.

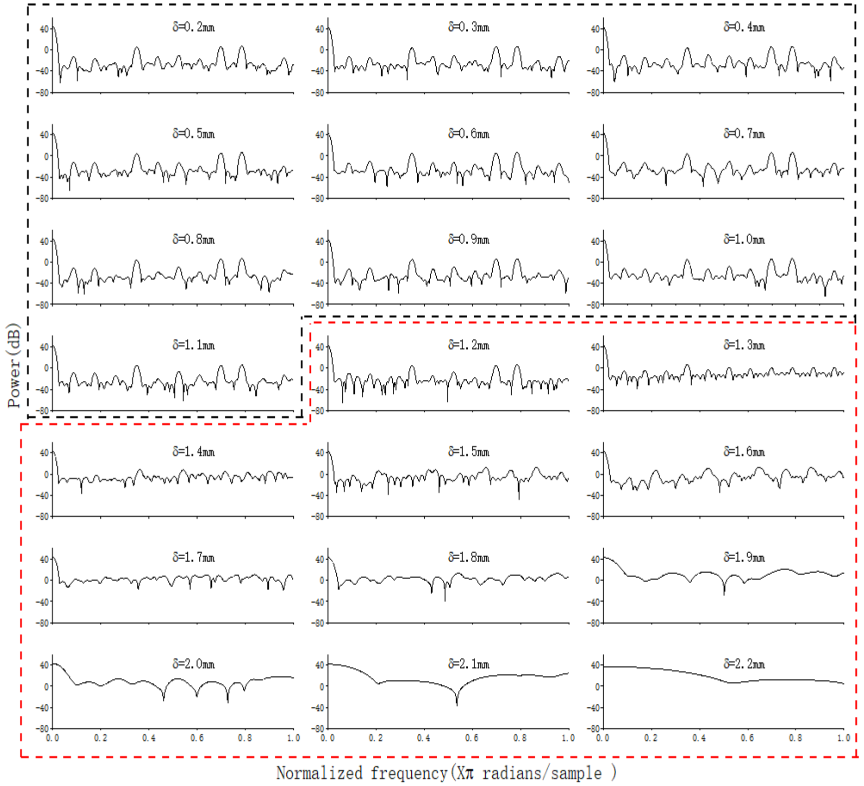
实验分析
Experimental Analysis

- 随着间隙增大，转速信号异常特征显现增加，异常信号出现频次增加。

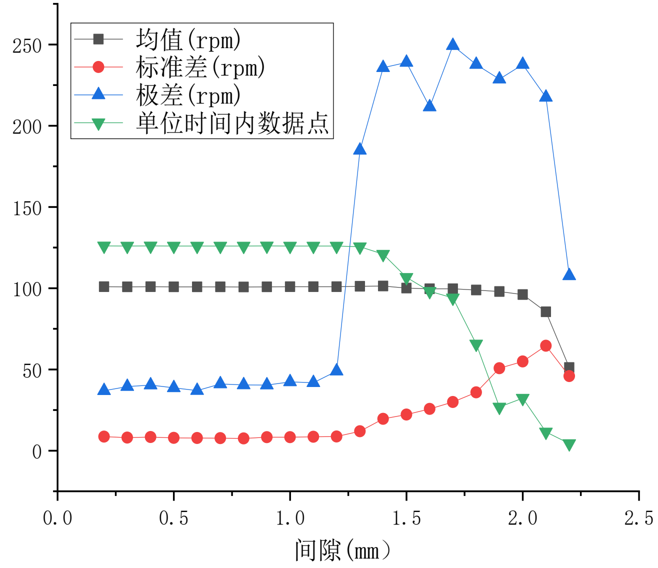
  As the gap increases, the abnormal characteristics of the speed signal increase and the frequency of abnormal signals increases.



采样频率为100kHz转速为100rpm下不同间隙的瞬时转速
Instantaneous speed of different clearances at sampling frequency of 100kHz and speed of 100rpm



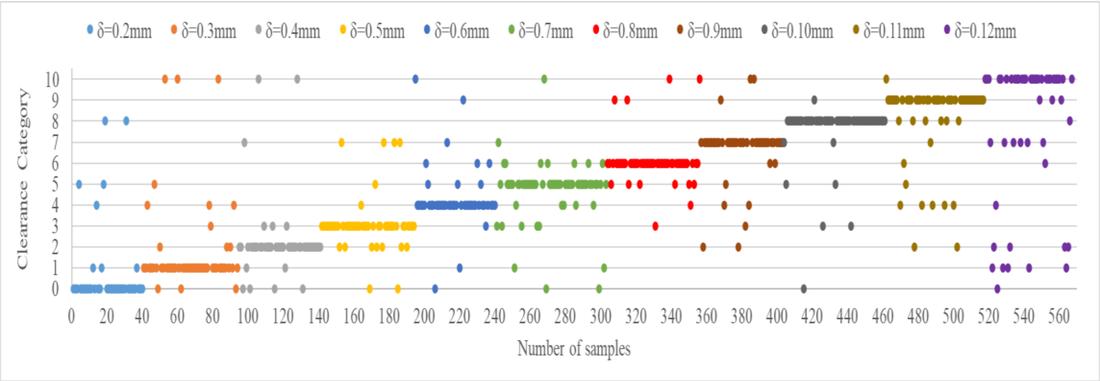
信号功率谱图
Signal power spectrum



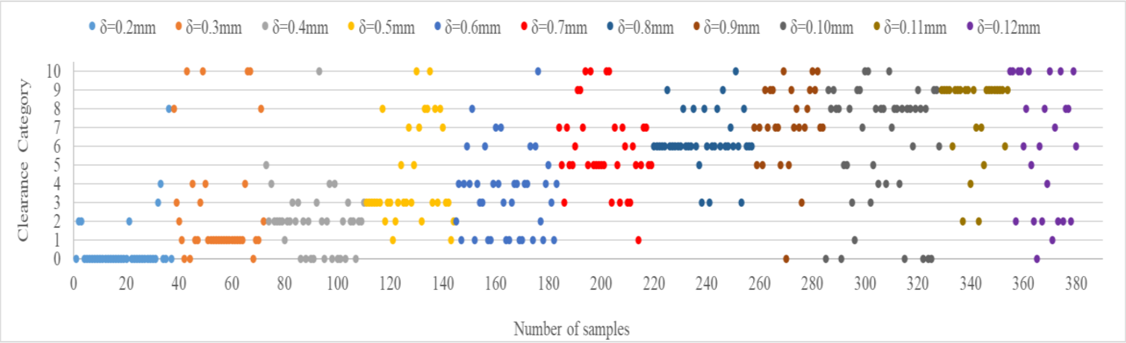
信号特征量
Signal characteristic quantity

小间隙对信号质量有区别，难以通过解析方法进行识别。
Small gaps have differences in signal quality and are difficult to identify by analytical methods.

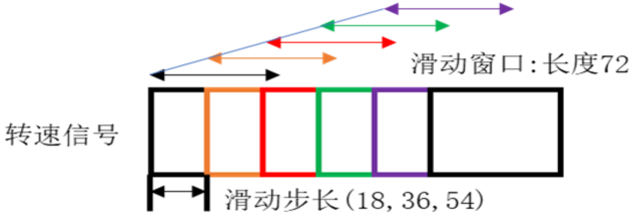
基于BP神经网络分析
Analysis based on BP neural network

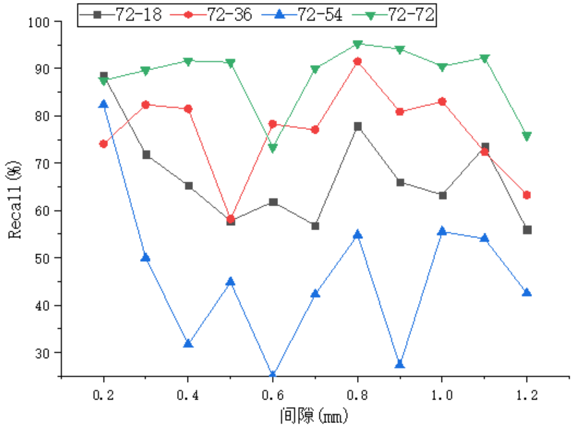


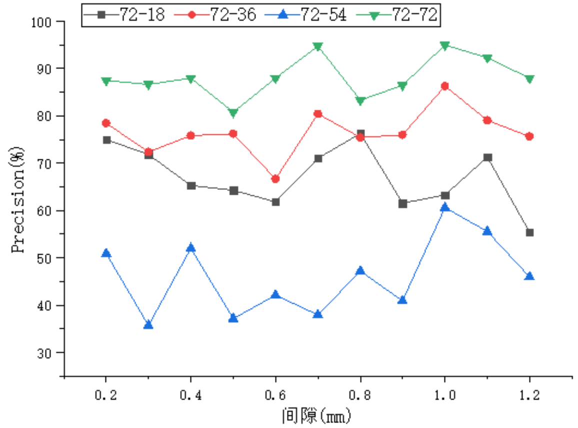
窗口长度为36的0.2-0.12mm间隙识别结果
Identification results of 0.2-0.12mm gap with window length of 36

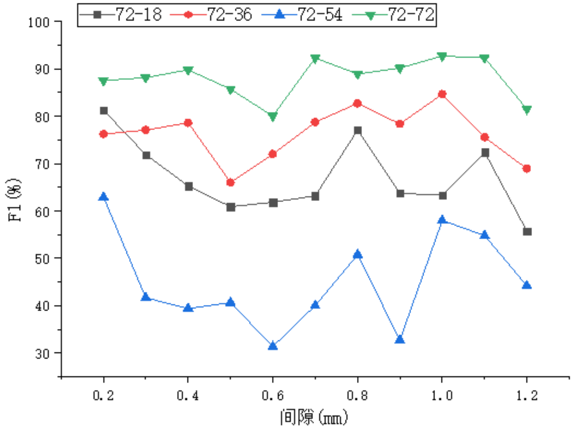


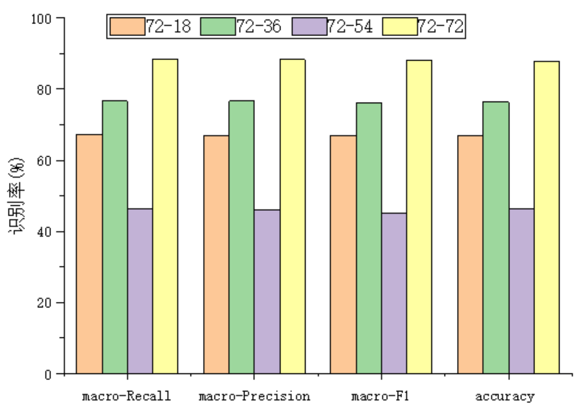
窗口长度为72的0.2-0.12mm间隙识别结果
Identification results of 0.2-0.12mm gap with window length of 72











- ➢ 数据不重叠即滑动步长为72时（一整圈）的识别结果较好
  The recognition result is better when the data does not overlap, i.e. the sliding step is 72 (one full circle);
- ➢ 小间隙对信号的影响可以被识别，即特征不明显依然可以被识别
  The effect of small gap on the signal can be recognized, that is, the feature can still be recognized if it is not obvious.

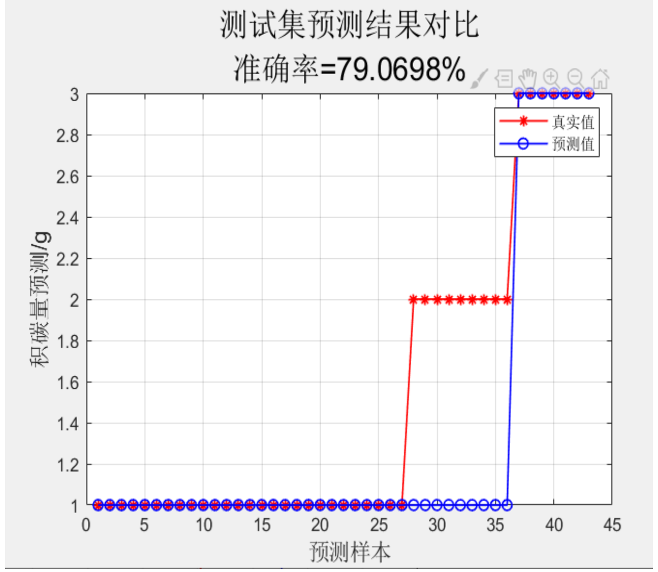
实践二　DPF的积碳量识别

Practice two Soot loading identification of DPF

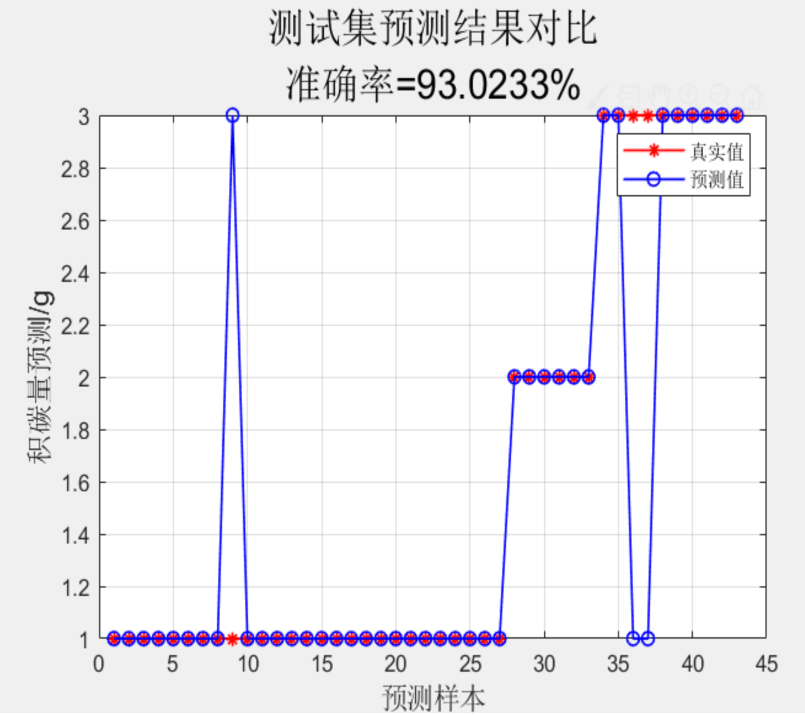
不同方式的数据融合
Data fusion in different ways

方法	优点	缺点
支持向量机 SVM	1.支持向量机SVM可以解决高维问题，更适合复杂数据集； 2.它对缺失数据不太敏感，可以提高泛化能力； 3.支持向量机SVM计算量小，模型不易过拟合； 4.它能很好地解决非线性问题。	1.对参数调整和核函数选择敏感，原分类器只适合处理二元分类问题，无需修改；2.非线性问题没有普适解，有时很难找到合适的核函数；3.对于大规模数据集，效率不是很高。
BP神经网络	1.具有较强的非线性映射能力； 2.具有高度自学习和自适应的能力； 3.具有将学习成果应用于新知识的能； 4.具有一定的容错能力。	1.BP神经网络结构的选择至今尚无一种统一而完整的理论指导，一般只能由经验选定； 2.随着训练能力的提高，预测能力反而会下降，也即出现所谓“过拟合”现象； 3.容易陷入局部极值，权值收敛到局部极小点，从而导致网络训练失败； 4.收敛速度慢； 5.难以解决应用问题的实例规模和网络规模间的矛盾问题，其涉及到网络容量的可能性与可行性的关系问题。
卷积神经网络 CNN	1.共享卷积核，对高维数据处理无压力； 2.无需手动选取特征，训练好权重，即得特征分类效果好。	1.需要调参，需要大样本量； 2.物理含义不明确（也就说，我们并不知道没个卷积层到底提取到的是什么特征，而且神经网络本身就是一种难以解释的“黑箱模型”）。

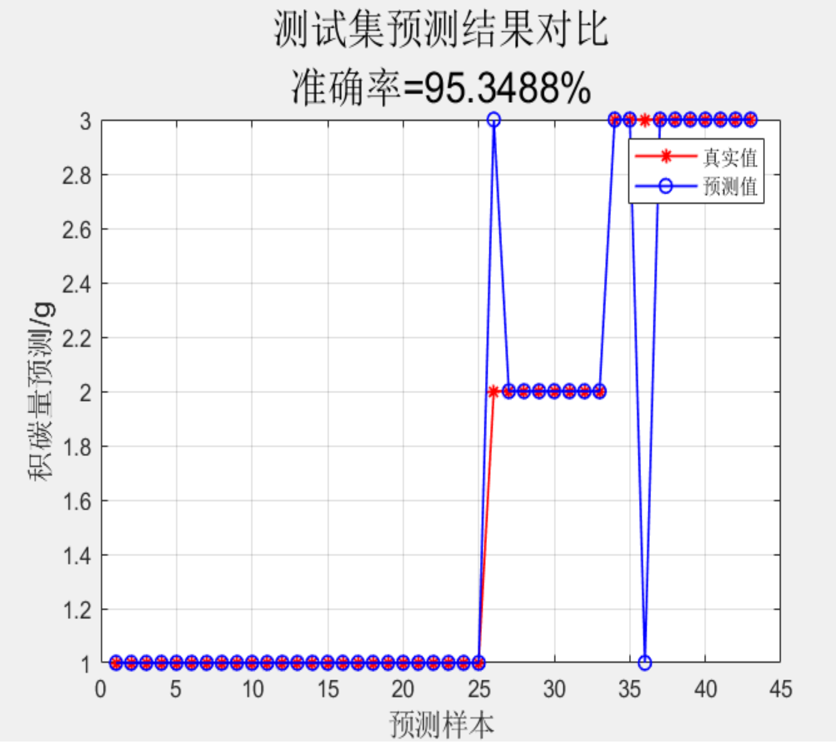
不同方式的数据融合
Data fusion in different ways



svm预测



BP预测



cnn网络预测

方法和数据质量都对结果有很重要的影响

Methods and data quality have a very important impact on the results

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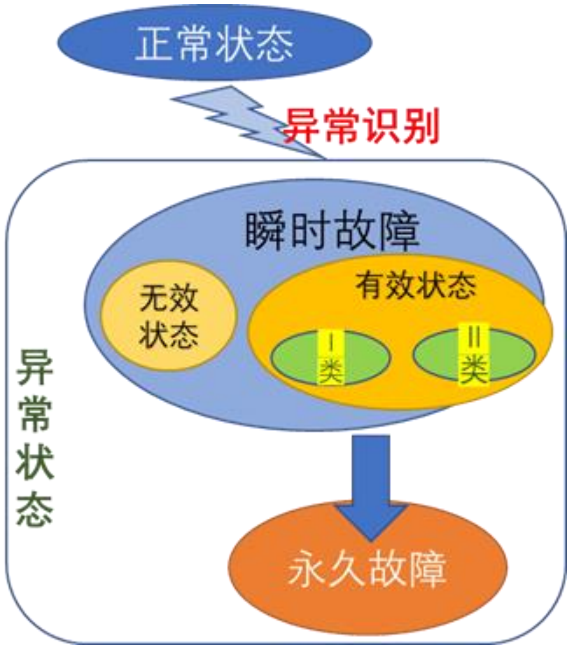
问题的提出
Questions raised



现状分析	故障 —诊断→ 故障检测 / 故障辨识 / 故障隔离 / 故障处理 ⟹ 重在故障的形成原因及故障定位上，并假定所监测信号出现异常即判断为故障
根源	只有出现故障后才能检测出 → 不能及早预防 干扰引起的异常可误判为故障 → 单次的干扰的误诊断
风险	故障识别的敏感性 → 若通过滤波消除干扰则容易较晚识别故障；若不滤波，则易受到干扰，形成误报
改进思路	研究故障形成过程，按照损伤强度来判断是否出现永久故障： 出现损失的表征 → 如何识别系统异常 损失的规律 → 如何根据瞬时故障确立永久故障
解决方案	识别瞬时故障特征方法 瞬时故障到永久故障故障管理 → 一类瞬时故障 / 二类瞬时故障 损伤强度阈值
价值	可以在提早预报的基础上降低误报

➢ 偶发异常不宜直接定义为永久故障
Occasional anomalies should not be directly defined as permanent faults.

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- 物理模型要选则合适的变量，从而利用虚拟的信号进行诊断；

  The physical model should select appropriate variables, so as to use virtual signals for diagnosis;

- 神经网络能在信号特征不明显处诊断，可将神经网络与物理模型相结合。

  The neural network can diagnose where the signal characteristics are not obvious, and can combine the neural network with the physical model;

- 异常信号不一定代表永久故障，应该开展瞬时故障的管理。

  Abnormal signals do not necessarily represent permanent faults, and transient fault management should be carried out.

谢谢！

Thanks！