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Multisensor information integration for online wear condition monitoring of diesel engines

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ABSTRACT

A diesel engine bench test was performed, and the online visual ferrograph (OLVF) and performance monitoring sensors were used to evaluate engine wear. The sliding window method was used to segment OLVF-monitoring data; features such as probability of smaller value and accumulated wear coefficient were extracted to clarify wear degree. The weighted combination multisensor information integration method was developed to calculate current engine condition factors. The results show that OLVF monitoring exhibits more sensitivity than other performance monitoring sensors. Using multisensor information provides an early warning of performance degradation ∼40 h before the diesel engine experiences a catastrophic fault.

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1. Introduction

An increasing number of automotive companies have begun using diesel engines in their vehicles owing to the worldwide focus on energy conservation and environmental protection. Diesel engines are complex, and they comprise thousands of parts. The wear of these parts leads to engine performance degradation, the monitoring and prediction of which has created a strong need for real-time, non-destructive testing of the wear status.

In recent times, numerous methods have been proposed for monitoring engine performance. Albarbar et al. [1] successfully used airborne acoustic signals to monitor injector conditions in an acoustically untreated laboratory. Li et al. [2] used vibration signals to identify the vital components of a diesel engine with abnormal clearance. Bueno et al. [3] developed a new measurement system for internal combustion engines. In their system, current polarized by a piezoelectric pressure transducer is converted into an analogue signal proportional to the cylinder pressure variation rate. However, these signals, which are collected from the engine, are complex and are often affected by background noise. Furthermore, some monitoring methods affect engine operation; for instance, in-cylinder pressure measurement requires a periodic reset of the charge amplifier to avoid saturation and is susceptible to interference. Some studies have, therefore, used multiple signals for monitoring. Barelli et al. [4] monitored acoustic and vibration signals to evaluate the operating conditions of internal combustion engines. Yang et al. [5] extracted the features of vibration and cylinder pressure signals and used a genetic programming method to construct a combined model to effectively identify the operating state of an engine valve. However, these methods remain ineffective until the engine fails. Thus, engine defect prediction has hitherto proved difficult. According to the second of the three axioms of tribology [6], the properties of tribological elements are time-dependent. Therefore, an abnormality in the above-mentioned signals often signifies equipment failure. Accordingly, a technique that monitors the time-varying characteristics of the wear status must be developed to provide an early warning of equipment failure.

Oil analysis technology can be used to non-destructively estimate the engine wear status. Spectrography and ferrography [7–10] can also be used to monitor engine wear. Recently, Xi'an Jiaotong University developed the online visual ferrograph (OLVF) for real-time engine wear monitoring [11–15], thus providing a promising approach for engine wear monitoring and life prediction. Another study [16] used OLVF to monitor the real-time variation in the debris concentration of piston rings and cylinder liners under different operating conditions. The relationship between the monitoring data and the operating conditions was examined. Ultimately, an approach for recognizing the engine health state was proposed. However, monitoring information may be incomplete when only a single sensor is used to monitor

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Nomenclature

tp	Length of sampling period of the performance parameters (s)
TF	Length of sampling period of OLVF (s)
$t_s(i)$	Start time of the ith performance parameter segmentation
$t_e(i)$	End time of the ith performance parameter segmentation
$YC(i)$	Pretreatment result for the ith initial performance parameter segment
$BL\ (i)$	Pretreatment result for the ith initial cylinder blow-by data segment
$T(i)$	Pretreatment result for the ith initial exhaust temperature data segment
NZ	Smallest IPCA value
P_{NZ}	Probability of the smallest value
NZL	Upper limit value of the smallest IPCA value
S_{NZ}	Number of NZ values within one IPCA data segment
S_{IPCA}	Total number of monitoring data points within one IPCA data segment.
$SSIP$	Accumulated wear coefficient within one segment
O_{RP}	Accumulated value of oil replenishment during the entire experiment
vop	Volume of oil pan
VK_{IPCA}	Multiplication factor of IPCA
γ	Increasing rate of IPCA value within required time $(fold)$
PBL	Probability of the fault being related to cylinder blow-by
BLS	Alarm threshold of cylinder blow-by
PT	Probability of the fault being related to the exhaust temperature
TS	Alarm threshold of the exhaust temperature
$P_1(t)$	Probability of the fault being related to P_{NZ}
ws_1	Alarm threshold of P_{NZ}
$P_2(t)$	Probability of the fault being related to $SSIP$
ws_2	Alarm threshold of $SSIP$
$P_3(t)$	Probability of the fault being related to $VK_{IPCA}(t)$
ws_3	Alarm threshold of VK_{IPCA}
$PIPCA(t)$	Probability of the fault being related to $IPCA$ at time t
$PY(i)$	Comprehensive state factor of the ith data segment
S	Correlation between the different signals and faults

the degradation of the engine health status. The above-mentioned studies did not integrate performance monitoring information with OLVF information to achieve a more comprehensive analysis. As a result, much useful information was wasted, and the relation between the engine's wear and health status was not clarified.

Several sensors can be used to monitor machine conditions. Many studies have, therefore, focused on multisensor information fusion methods. Basir et al. [17] employed the Dempster–Shafer (DS) evidence theory to model and fuse multisensory pieces of evidence pertinent to engine quality. Seraji et al. [18] focused on multisensor and multi-decision fusion methods (fuzzy, Bayesian, and DS) for terrain safety assessment. Wang et al. [19] presented a new condition-based maintenance decision system that employs data fusion to improve evaluation accuracy and reliability. They have also employed the Bayesian linear model and gamma process. However, previous studies did not compare and analyse the advantages and disadvantages of different monitoring parameters. Furthermore, they did not assign weights for different monitoring parameters.

To improve the accuracy of wear monitoring for diesel engines, the current study adopted OLVF to monitor the engine wear condition. The cylinder blow-by and exhaust temperature during engine operation were monitored. Features were extracted, and the sensitivity of different monitoring signals to the engine health status was compared. OLVF monitoring information was considered the primary information, and other performance monitoring information was considered auxiliary information. A combined weighted model was constructed to integrate multisensor information and subsequently provide an early warning of the engine health status. The reliability of the monitoring method was verified experimentally.

2. Index for diesel engine wear health status evaluation

Several monitoring signals were selected to evaluate the engine health status. In particular, cylinder blow-by and cylinder exhaust temperature were selected to monitor the engine performance, and OLVF was used to monitor the diesel engine wear status.

2.1. Cylinder blow-by

Piston and cylinder wear leads to an increase in cylinder blow-by; in this study, the blow-by passage of the engine includes the ring gap and the air gaps caused by cylinder scoring.

2.1.1. Blow-by gas flowing through ring gap

For a piston ring to be fitted into the 'grooves' of the piston, it is designed to have a break at one point on its circumference, as opposed to being continuous. When fitting new piston rings within an engine, the end gap of the ring should be within recommended limits, called the ring gap, as shown in the left-hand side of Fig. 1. The assumption that the leakage area of the ring is two times larger than the ring gap is not significantly different from the actual situation [20]. Cumulative wear and aging of the engine increases the ring gap. Too large a gap may lead to unacceptable compression and levels of blow-by gases or oil consumption.

2.1.2. Blow-by gas flowing through the air gaps caused by cylinder scoring

When the piston ring and cylinder liner are subjected to serious wear, the inner wall of the cylinder liner is scratched. This

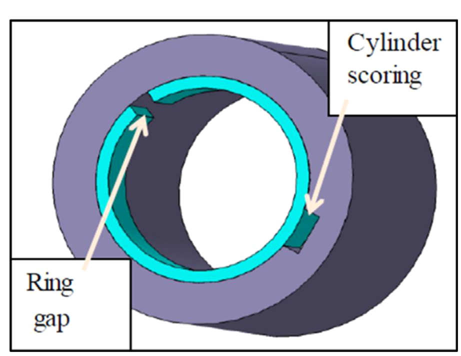

Fig. 1. Schematic representation of the blow-by passage of the piston rings and cylinder liner.

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