Real Time Monitoring System for Automotive Tire Set using an Acoustic Signal

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Abstract: In this research, we present a real time monitoring system for Automotive Tire Set (ATS) using an acoustic signal. Order tracking techniques applied in signal processing module by using the recursive Kalman adaptive filtering algorithm which can be used to exact the order amplitudes of global acoustic signals. The detective system combines a signal processing module and orders amplitude calculated of feature extraction. On the basis of acoustic signal extraction to distinguish between normal and abnormal types can be used to acquire high resolution amplitude of different orders. The diagnostic process is based on recording the drive shaft of tire speed. This system is implemented on the platform of National Instruments (NI) compact-RIO and c-series modules. Instantaneous shaft speed and acoustic signal are respectively detected by means of fiber optical and array microphone. Experimental results were carried out for a practical Mitsubishi Freeca Car to appear obviously the effectiveness of the proposed system in tracking the ATS orders with high recognition rate. An intelligent prediction integration system with internet (IPII) for ATS was proposed.

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1 INTRODUCTION

In recent years, issues like green energy and Internet of Vehicles (IoV) (He et al., 2014) developed with a large amount sensors to detect the predictive faults. The firms may achieve advantages of fast production, small-volume production of a wide range of different items, and great cost reduction, etc., which are the promotion cores of Taiwan government's Productivity 4.0 plan The IoV concept is also included in it, they called Internet of Everything (IoE). The vehicles are now becoming more and more complex with increased reliability on electronics and on-board computers. Hence, fault diagnosis on engines of vehicle has become increasingly challenging with a great number of parts and systems. Therefore, the job of fault diagnosis of vehicle has become more difficult, particularly for nonroutine faults. Automotive manufacturers develop a new electronic diagnostic systems which can help lead quickly to the root of vehicle faults. Because of the limited resources of a vehicle (less information storage and slow processor) for electronic diagnostic apparatus, it is difficult to do much more than limit type diagnostics. Advanced signal processing techniques are employed and expanded as signal transformations or machine learning techniques.

Generally speaking, procedure of operating on internal combustion (I.C.) engine belongs to rotating machinery in mechanical system. The classifications of fault in rotating mechanical system are resonance, bearing fault, power unbalance, gear fault, and so forth. Recently, fault diagnosis of rotating machinery in automobile is based on shaft speed signal and vibration signal to monitor the conditions of system. The vibration energy or pressure energy are often exploited in fault diagnostic system which can be monitored the conditions of vehicle engine when damage is increased. On the other hand, the acoustic energy produced by rotating machine usually reflects the working condition. An

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experienced technician can make the troubleshooting by means of listening to the sound of machine. A diagnostic system using acoustic energy will directly diagnose in rotating machine. In order to obtain the useful information by using an acoustic energy for feature extraction is based on signal processing techniques when the heavy noise is increased around the rotating machinery.

The features of fault diagnosis in an I.C. gasoline engine can be monitored by measuring the vibration signal, acoustic signal or pressure signal at specific locations, e.g. engine mounts. Among these signals mainly comprised a basic frequency with related to harmonic frequencies, most of which correlates with revolution of crankshaft of engine. The acoustic energy or vibration energy is exceptionally increased when the translation systems are harmed. In general, a traditional diagnosis method is used to observe the amplitude difference of energy in time-frequency domain for fault diagnosis. For instant, the fast Fourier transform (FFT) methods are used to observe the amplitude difference in time-frequency domain at the fixed speed. However, the information thus obtained is only partial because some features of fault do not respond significantly at the fixed operation speed. Hence the smearing problem generally arises in practical implementation particularly at various speeds.

A well-known approach is also utilized, the order tracking technique that exploits acoustic energy or vibration signals, supplemented with information of crankshaft speed, serves as a useful tool for diagnosis of the vehicle engine. The comparison between frequency analysis and order analysis is summarized in Table 1. In general, conventional methods of order tracking are mainly based on a Fourier analysis. A high resolution order tracking technique is proposed in order to overcome the smearing problems arising. Recently, fault diagnosis of order tracking technique has become one of the significant approaches in rotating machinery. Using the order tracking technique can provide the feature of order spectra from vibration signal and shaft speed for an I.C. engine. Moreover, an order spectrum gives the amplitude of signal as a function of harmonic and crankshaft speed (R.P.M.). Order tracking is mainly used to analyze and track the energy of order signal from dynamic signal. However, generally tracking methods are ineffective for applications including the multiple independent shaft speeds. For instance, the shaft speed of an I.C. engine and the speed of cooling fans are independent. If one calculates the orders based on either speeds, the signals related to other speeds would appear as uncorrelated noise and reduced the tracking accuracy of the results. In order to avoid aforementioned problems encountered, the representative model-based methods have been proposed, such as an adaptive Kalman filtering method. In 1996, an adaptive filter theory is published by Haykin (Haykin, 2002), discussed some conclusions for adaptive filtering methodologies and order tracking techniques in fault diagnosis of rotating machinery.

In this work, a high resolution order tracking fault diagnosis technique (Wu, et al., 2009) is proposed for tracking the signals of acoustical energy of an ATS set. This technique exploits adaptive filtering based on the Kalman filter algorithm, the proposed methods also requires the information of shaft revolution of ATS and measured by a fiber optical sensor. In this technique, order amplitudes are calculated off-line by using a least-squares approach. The adaptive algorithm is essentially sample-based and the order amplitudes can be calculated in a real-time fashion for fault diagnosis of ATS. The technique is implemented on a NI cRIO 9075 platform for evaluating the performance in practically diagnostic systems. On the other hand, the information of vibration signal is the most widely used in the diagnostic analysis of fault. In the case of fault diagnosis application systems by using the vibration reference signal may not be available. As a result of effect of uncertain conditions around the vehicle ATS can likely be generated as the additional vibration delivered from the ground. Thus, a sound acoustical signal provides accurate information to the fault diagnosis system.

This research scope is mainly a solution for ATS, which integrates the sensing and predicting technology of rotary equipment, order analysis theory, NI cRIO embedded hardware, Real-Time Module, FPGA, and PC-Based Guide User Interface, etc., and the major purpose is to provide the real-time statuses of rotary equipment. This paper issued an Intelligent Prediction Integration System with Internet, IPII. ATS set play a significant role in vehicle, therefore a sudden broken is unfavourable; and the intelligent sensing system application can not only maintain the operating conditions at the best status to hold life of people. Figure 1 is the simulation fixture of an intelligent sensing module system.

For the proposed method, a sound acoustical signal is exploited to evaluate the proposed algorithms. The results indicate that the proposed method is well suited for the tracking of closely spaced orders or crossing orders without significant smearing problems. Experiments are carried out to evaluate the proposed system with practically running tests under fixed revolution conditions The filtering algorithms and the order tracking techniques will be described.

Table 1: Relationship of frequency and order analysis.

Frequency analysis	Order analysis
Time [sec]	Revolutions [rev]
Frequency [Hz] [per sec]	Harmonics [Order] [per revolution]

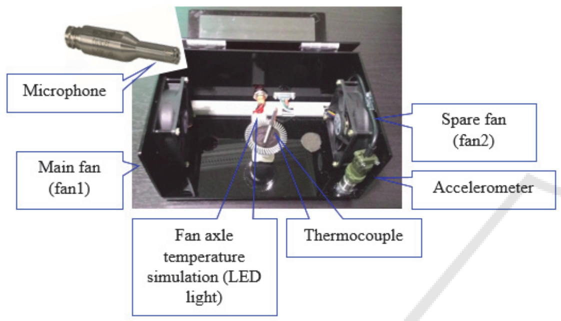

Figure 1: Simulation fixture of ATS.

2 THEOREY OF ORDER TRACKING

The speed, acoustics, and vibration signals of rotary machinery must be calculated, then one transfers the discrete time signals to discrete angle signals. Discrete time signals are acquired according to equal time intervals while discrete angle signals are sampled by equal shaft angles, and this is the so-called Resampling theorem. Angle-Samples can be acquired by hardware devices or software post-processing.

The hardware solution can achieve the equal angle interval sampling purpose by using Encoder or Tachometer's impulse signals to trigger Analog-to-Digital Conversion. And this sampling method requires extra hardware devices and complex-numbered analog filters, which is not easy to implement. Hence this paper adopted the software post-processing method for the experiment. The method first collects vibration signals and tachometer's impulse signals at the same time to interpolate or Curve-Fitting tachometer's impulse signals to receive relative angular displacements at each time point, then to sample vibration and acoustic signals based on the equal angular displacement principle.

The resampled signal are called Order Signal, and the spectrogram acquired from having FFT or STFT on Order Signal is called Order Spectrogram which enables one to easily tell Fundamental Frequency and Harmonies from the analyzed signals, and helps to analyze acoustic signal features.

2.1 Kalman Filtering

The signals generated by rotary machinery are Frequency-Modulated Signal, which usually contains various frequency elements (main rotary frequency or its harmony wave). Therefore, signals can be presented by Superposition with sinusoids of different frequencies, and we used adaptive Kalman filter to implement big data computing of rotary equipment, and the Data Equation is the part of sensed speed, acoustics data or estimated energy, the flat condition of estimating order is called Structural Equation. An Kalman filter algorithm presented solutions by using State-Space, and is also able to be resolved by recursive method.

The acoustic signal $x(t)$ containing k orders generated by the rotating shaft from an engine platform can be expressed as

$$x(t) = A_1\cos[\theta(t)+\phi_1] + A_2\cos[2\theta(t)+\phi_2] + \cdots + A_k\cos[k\theta(t)+\phi_k] \quad (1)$$

where A_k and ϕ_k express the amplitude and phase, respectively, of the kth order, and the variable $\theta(t)$ denotes the angular displacement of the shaft computed by the following integral

$$\theta(t) = \int_0^t \omega(\tau)d\tau = \int_0^t 2\pi f(\tau)d\tau \quad (2)$$

where $\omega(\tau)$ represents the instantaneous angular frequency (rad/sec) of the ATS shaft which should be calculated by numerically integrating the instantaneous angular frequency measured by the fiber optical sensor from ATS shaft. The block diagram representation of the adaptive Kalman filtering is shown as Figure 2, which the procedure is summarized as follows

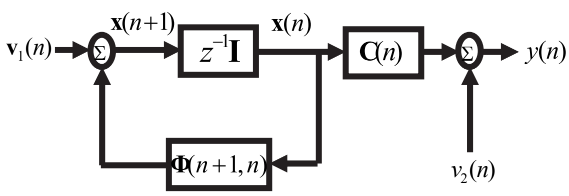

Figure 2: Block diagram of Adaptive Kalman filtering.

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The procedure is summarized as follows

$$\mathbf{K}(n+1,n)=\mathbf{F}(n+1,n)\mathbf{K}(n)\mathbf{F}^{H}(n+1,n)+\mathbf{Q}_{1}(n) \quad (3)$$

The equation (3) can be represented a *Riccati equation solver* for computing the updated value $\mathbf{K}(n+1,n)$. To initialize the Kalman filtering process, the initial conditions are generally taken to be: $\hat{\mathbf{x}}(1\,|\,\mathrm{y}_0)=\mathbf{0}_{(4k+2)\times 1}$ ($4k+2$ is the number of parameters $A_i(n)$), $\mathbf{K}(1,0)=\mathbf{I}$ ($\mathbf{I}$ is a ($4k+2$) × ($4k+2$) identity matrix. Thus in applying this order tracking method, different shaft speed of axles must be available. However, the prior information of the number of order and resonance frequency is also required. Technically, this can be obtained by a preliminary scan by using conventional order tracking methods. If this can be done, the proposed technique should provide results with improved accuracy for prediction system on a ATS. The IPII monitoring structure of ATS is shown as figure 3.

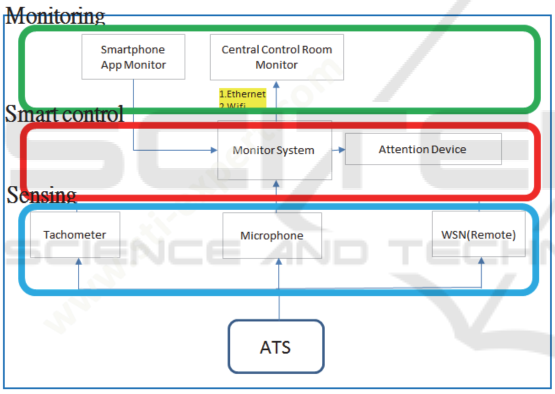

Figure 3: Structure of an IPII.

3 RESULT AND VERIFICATION

The research is mainly based on applying multi-sensor big data algorithm, and uses acoustic, speed, and temperature, etc. to sense signals to extract and analyze then determine, figure 4 shows the intelligent ATS experimental structure which includes sensors from ATS system, fiber optical tachometer to microphone and the system module is an embedded 667MHz CPU, with an adaptive Kalman filter for kernel algorithms.

The IPII system was set to sample frequency at 5 KHz; the extraction time was 12 seconds; FFT Record Length was 2,048 points; Hanning window function. Figure 5 is the user interface which can

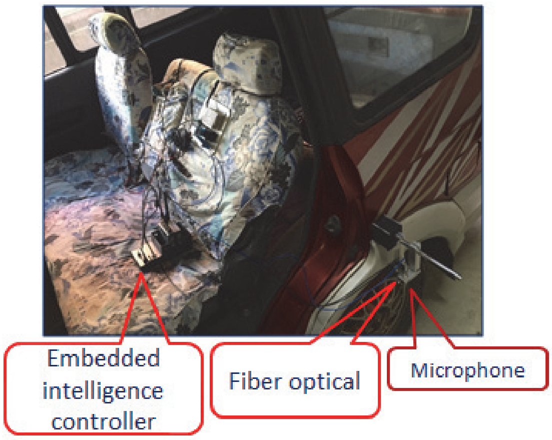

Figure 4: Intelligence ATS structure.

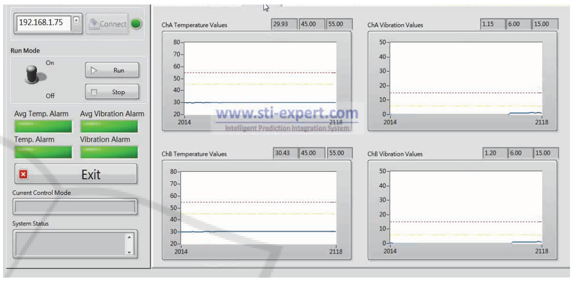

Figure 5: IPII GUI.

operate the ATS equipment on CPU end, and is able to link to tablets and continue serving. Figure 6 shows the fiber optical from the ATS condition, the on-line microphone measures the feature shown as figure 7-8. Figure 9 is shown as the time signal of practical microphone.

All the sensors with the network device, as well as a microphone to perform big data real-time computing, there was an axle failure, thus figure 10 shows the big data computing result of the acoustic energy; the solid line is about normal energy distribution condition of the ATS condition.

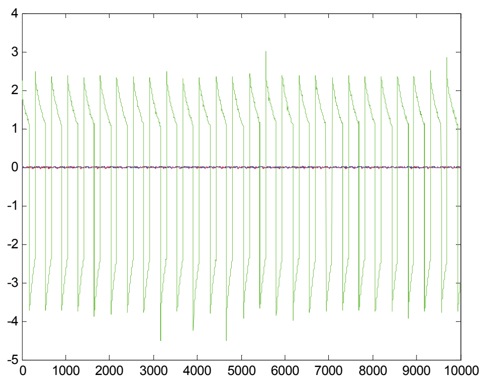

Figure 6: ATS signal from fiber optical.

This paper applied an adaptive algorithm, and with the network device, one can learn real-time condition of the current rotary equipment, then to monitor, predict, and adjust the equipment status in time, which also meets the predicting and sensing technology of Taiwan's Productivity 4.0 plan.

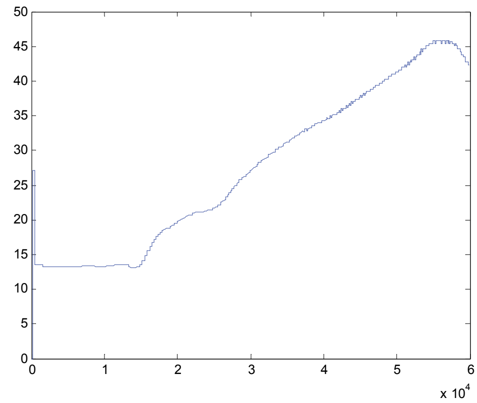

Figure 7: ATS signal from fiber optical.

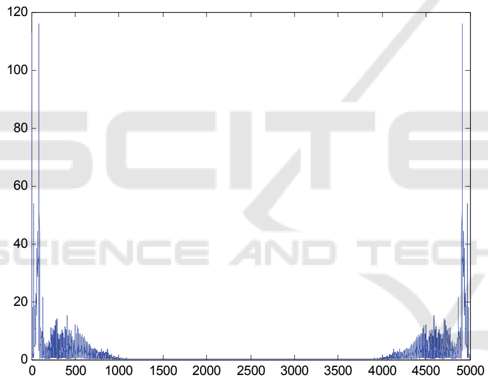

Figure 8: FFT spectrum with microphone.

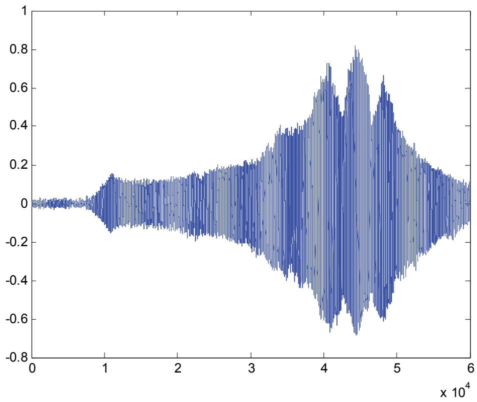

Figure 9: Time signal from microphone.

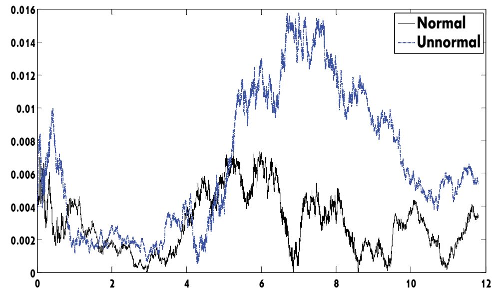

Figure 10: Adaptive Kalman filtering algorithm by using acoustic energy (the dotted line represents a failure condition while the solid line represents a normal condition).

4 CONCLUSIONS

A real time monitoring system for Automobile Tire Set (ATS) using an acoustic signal was proposed. The point of Taiwan's Productivity 4.0 plan is how to plan prediction technology, smart factory, IoT, and IoV; distributing predicting sensors and the function of real-time computing and predicting are implemented in this paper, also, by using intelligent LAN devices, one can instantly monitor the ATS with IPII.

The practical sensing of acoustic and fiber optical signals real-time computing and the adaptive order theory successfully predict the system condition of the ATS before a breakdown, which helps the follow-up maintenances and alarm instruction. This paper brought up intelligent ATS equipment based on fiber optical and acoustic signals, which can effectively monitor various operational conditions of ATS. The IPII system uses acoustic signals to predict the shap, tire depth features of ATS, so that the losses can be reduced to the minimum before the vehicle accidents.

The result of the experiment proved that the adaptive order analysis method was an effective diagnosis to be applied on intelligent ATS real-time prediction; however, the amount of feature energy value shown by each big data order needs to be distinguished by applying an intelligent ambiguous system, and the order sampling number of every condition must be taken into consideration, five samples at least, to increase the accuracy of the identification rate.

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