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Development of a Wireless Testing System for Automotive Multistage Mechanical Transmissions; a Smart Diagnostic System for Condition Based Maintenance

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Abstract: Power transmissions are one of the most important parts of any mechanical system. In order to achieve the reliable operation of these systems, effective maintenance strategies must be used. Predictive health monitoring (PHM) and condition based maintenance (CBM) strategies are currently gaining in popularity due to their effectiveness in reducing maintenance costs; however, these require reliable monitoring techniques such as vibration analysis, acoustic emission, oil debris analysis and thermal analysis. This paper different monitoring features have been studied in order to develop an online monitoring tool that able to track the condition of an operating transmission system, classifying faults, and detect the onset of failure. The study presents an online PHM system utilising autoregressive (AR) parametric method algorithms based on vibration data. The online monitoring algorithm can support CBM and PHM of automotive multistage manual transmissions. The design, operation and validation of the online system are described and demonstrated. The results of the experimental test prove the system's capability and support the recent trend of using CBM and PHM strategies.

Keywords: Mechanical transmission, condition based maintenance, vibration analysis, health monitoring system, autoregressive.

1. Introduction

Monitoring the condition of the in-service mechanical transmission system is an important issue for reliability, where their components deteriorate over the time and affected much when subjected to varying loads. This is led in continues improve of maintenance strategies from breakdown and periodic maintenance to CBM and predictive maintenance in order to sustain reliability and reducing the periodic maintenance costs. Also, in some applications there is more demanding aspect such as saving man's life other than reliability [1]. Smith [2], has defined the causes of transmission vibration and its transmission path, including factors such as manufacturing error, design error and gear tooth deflection, which combine to introduce a transmission error (TE), which is the primary source of the vibration.

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Over the past decade, vibration analysis proved to be a trustworthy diagnostic technique that can provide reliable information. However, in the last 10 years researchers devoted a much effort to support CBM actions using vibration information [3-13]. The work focused on the development of reliable features using a suitable signal processing techniques can be grouped in two groups; time domain vibration features including: statistical parameters, time synchronous averaging based methods, filter based methods, stochastic methods and other model based methods. The second group is the frequency domain and time frequency domain features including: first order; (FFT), correlation of spectrum, signal averaging, short time Fourier transform (STFT), continuous wavelet transform (CWT), discrete wavelet transform (DWT), discrete wavelet packet analysis (DWPA), time-averaged wavelet spectrum (TAWS) and time-frequency scale domain (TFS). Second order; power spectrum, Power cepstrum (logarithm of Power spectrum), cyclostationarity, spectrogram Wigner distribution and scalogram. Third order; Bicoherence spectrum, bilinearity and Wigner bi Spectra. Fourth order; Wigner tri Spectra [29].

The authors of this paper continued their research by developing multi sensors fusion algorithms to fuse vibration analysis information with other sensory data, such as acoustic emission and oil debris analysis to minimise false alarms that may occur in failure prediction [14-17]. Also, other researchers devoted efforts to build intelligent algorithms based on vibration features including Expert systems, ANN's , Genetic algorithm, and fuzzy logic [18 - 28]. Intelligent health monitoring systems incorporate AI algorithms, where AI can be defined as "the science of making machines do things that would require intelligence if done by humans" [33]. To develop an IHMS, the running system condition must be recognized and classified. Researchers have devoted considerable effort to the application of various different soft computing methods to develop IHMSs, and have shown that this can be achieved using methods such as neural networks, fuzzy logic and mathematical modelling based on parametric approaches. All of these methods can provide important tools in the field of intelligent systems which can learn, adapt, and make decisions concerning the system they are in charge of [33].

Artificial neural networks (ANNs) have been used with different HMS techniques such as vibration and acoustic monitoring. An ANN requires input data of the healthy and faulty conditions to be pre-processed, and then these features are used to model the system's behaviour. Fenton et al [36] mentioned that there are two main basic network architectures: feed-forward and recurrent ANNs. Feed-forward ANNs do not have feedback between layers, and previous inputs are not remembered, whereas recurrent ANNs involve feedback between layers and previous inputs are remembered and can be used to reconstruct correlative memory. The two standard neural network architectures used in transmission diagnostics are the feed-forward back propagation network, and the Kohonen feature map which is also known as the self organizing map (SOM) [37]. Fuzzy logic was developed by Zadeh in the 1960s to characterize types of knowledge that cannot be represented by classical Boolean algebra to cover approximate knowledge in describing the behaviour of systems which are difficult to describe mathematically [33].

Currently, the authors of this paper is devoting their efforts in developing smart CBM systems that can use one analysis technique only such as vibration or acoustic emission analysis along with intelligent algorithms to predict the onset of failures; this is to reduce costs of different sensory requirements [30-32]. This paper builds on the author's previous work to develop an online wireless vibration analysis tool for testing automotive mechanical transmissions. The online operation of this system can lead to the wide spread of using such systems with other rotating machinery.

Parametric methods based on mathematical modelling is to fit measured time series waveform data to a parametric time series model, and then extract features based on this model [34]. Two models are currently in use: the auto regressive (AR) and auto-regressive moving average (ARMA) models. The advantage of mathematical modelling based on parametric methods over the neural networks model-based method is its ability to deal with time series data directly without the need for a signal pre-processing step to extract useful features that can be modelled to represent the system [14]. However, they can only be used to model a time series signal such as a vibration signal, and cannot be applied to combined information from several techniques (vibration, AE and ODA) such as in the case of fuzzy logic.

3. Design and Implementation of a Testing System for Automotive Mechanical Transmissions:

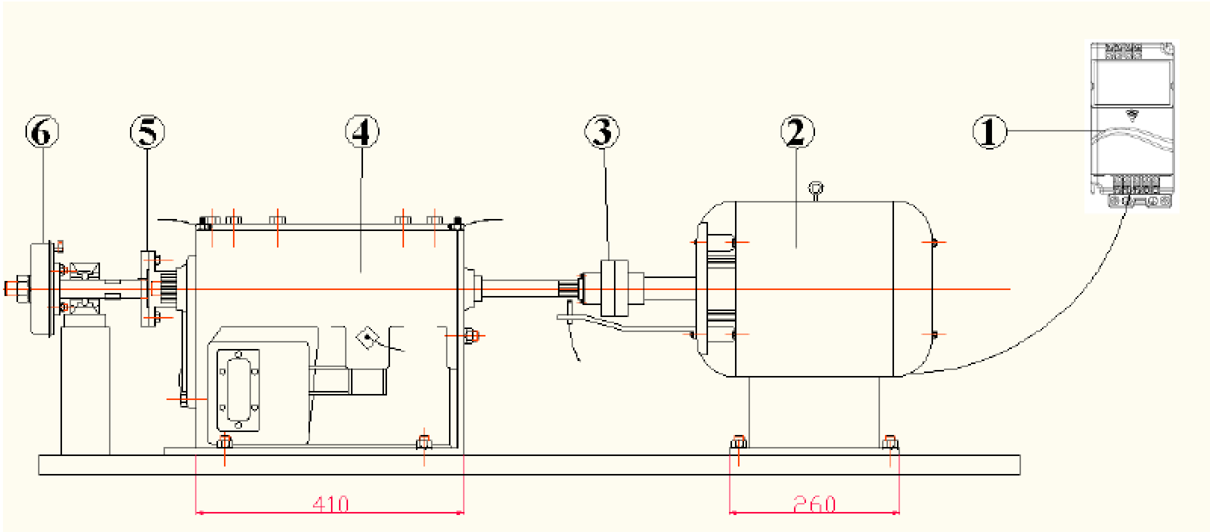
An automotive mechanical transmissions gear test rig is currently being developed for this on-going research. The rig comprises 130mm centre distance gearbox. Table1 provides the basic geometry specification for the gears. The system is driven by a 7.5Kw variable speed electric motor controlled by an inverter to provide a speed variation of 1750 rpm. The load is applied via a mechanical breaking mechanism.

Table 1. Gears basic geometry

Specifications	Gear number									
	1		2		3		4		5	
	P	W	P	W	P	W	P	W	P	W
Module (mm)	9.5	9.5	9.5	9.5	8	8	8	8	8	8
Gear Type (H-S)	S	S	H	H	H	H	H	H	H	H
Number of teeth	21	40	19	35	30	33	38	25	43	20
Face Width (mm)	25	25	25	25	25	25	25	25	30	30
Gear Ratio	4.095		3.96		2.365		1.414		1	

The rig can generate a load torque on the test gears in the range of 0 - 200Nm. The torque is measured using calibrated strain gauges installed on the shaft and the measured torque values are transmitted to the control program by telemetry in order to provide torque control of the loading mechanism on the mechanical transmissions. The test rig is shown in Figure 1. The testing system has been developed for this research work, and is capable of on-line monitoring, automatic measurement, and analysis. Also, any changes in the gears and bearing conditions due to degradation during the operation can be identified. The advantage of developing the system arises from its ability to enhance online analysis methods for vibration technique to provide robust information about the system's condition.

Two temperatures were measured: gearbox oil temperature and bearing temperature using RTD temperature sensors (10mv/C). The input shaft speed and motor current were also monitored as a precaution. The test rig operating conditions were monitored and it is flexibly changed according to the required test conditions using LabVIEW's virtual instrument scalable architecture features.

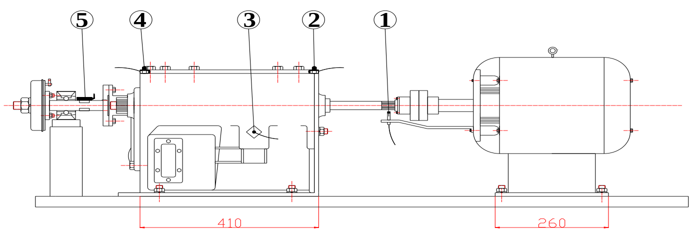


1. Inverter, 2. Electric motor, 3. Fixable coupling, 4. 130 mm centre distance Gearbox, 5. Mechanical coupling, 6. Loading Mechanism

Fig.1. Test rig layout

The Vibration analysis system incorporated a 24-bit NI wireless DSA data acquisition card (NI 9234 with cDAQ-9191) to acquire the vibration signal, speed and temperature. The vibration signals were acquired using two DJB Piezotronic constant current source accelerometers (model no. Acc103 -10mV/g) mounted adjacent to the tested gear bearings transversely to the gearbox casing, and a shaft speed sensor was used to acquire the shaft rotation reference. The sensors location diagram over the test rig is shown in Figure 2.

The vibration signals are then acquired continuously and transmitted to the base unit using an IEEE 802.11b/g (Wi-Fi) wireless communication interface (frequency range 2.412–2.462 GHz). The system can send the data from a range up to 30 m for indoor measurements and 100 m for outdoor operation as long as the line of sight of the wireless signal is provided. The system can also provide Ethernet cabling measurements up to a distance of 100 m. The test rig sensor-actuation system layout is shown in Figure 3.



1. Speed sensor
2. Accelerometer 1
3. Temperature sensor
4. Accelerometer 2
5. Torque sensor

Fig.2. Sensors location layout

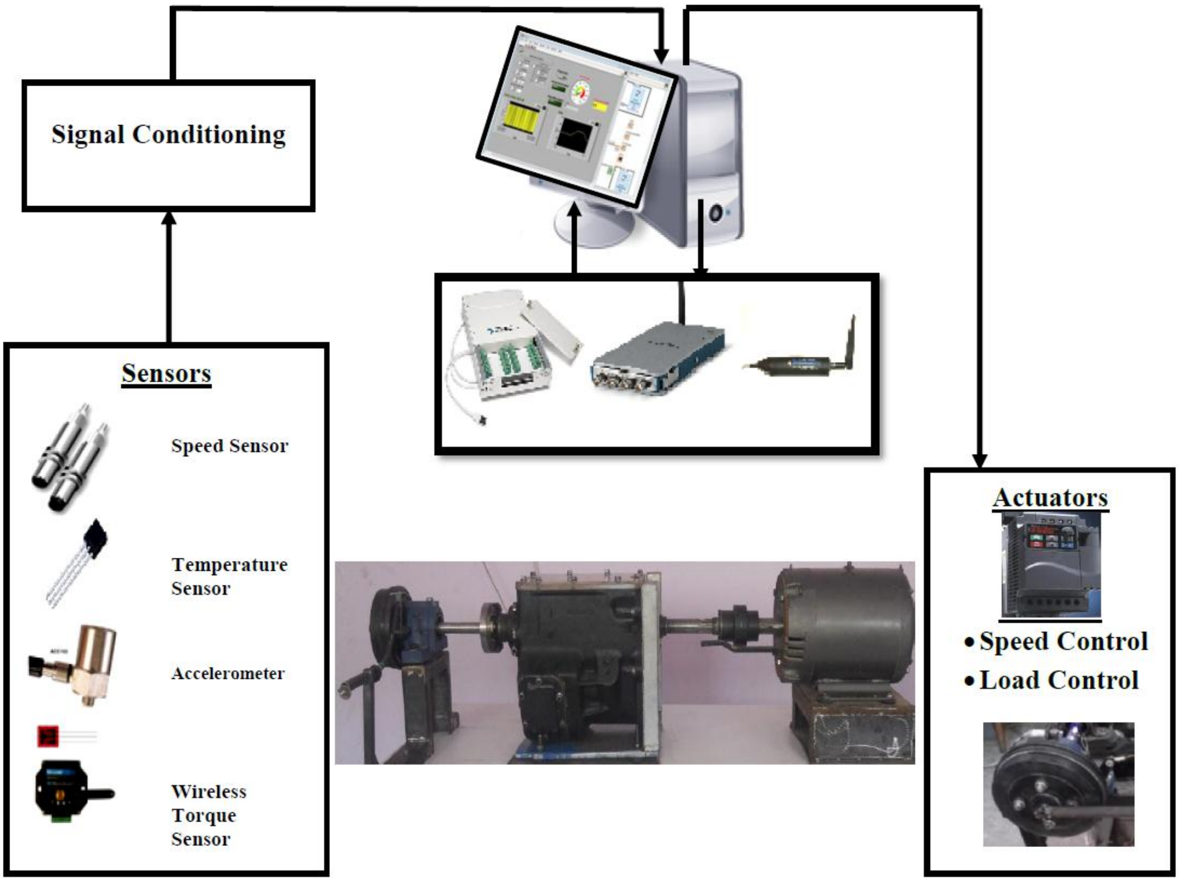


Fig. 3 The test rig sensors - actuation system layout

4. Design and Implementation of Smart Vibration Analysis Software for Automotive Mechanical Transmissions Testing:

The reduced set of vector parameters of these models are used to describe the system data required. The method is based on matching the model to a specific data type, such as data from a healthy transmission, and any change in the signal characteristics due to failure will change the statistical properties of the output [35]. Samuel and Pines [34] discussed the differences between various types of parametric method, explaining the AR and ARMA models as follows.

The AR model for a time series X can be represented by a linear regression of X on itself plus an error series which is assumed to be noise having a Gaussian distribution. The AR model is given in Equation (1).

$$x_i = -\sum_{k=1}^{p} a_k x_{i-k} + e_i \tag{1}$$

where p is the model order and provides the number of past inputs required to model the signal, which is determined experimentally, a_k are the AR coefficients, i is the sample index, and e_i is the Gaussian error series [34].

The ARMA model is a generalized form of the AR model that can represent a time series *X*. The ARMA model is given by Equation (2).

$$x_i = -\sum_{k=1}^{p} a_k x_{i-k} + \sum_{k=0}^{q} b_k e_{i-k} \quad (2)$$

where p and q are the ARMA model order, a_k are the AR coefficients, b_k are the MA coefficients, i is the sample index, and e_{i_k} is the model error series. The MA coefficients b_k have to be computed after the AR coefficients are determined, hence the AR approach has a computational advantage over the ARMA approach [34].
The smart vibration analysis system software is developed in the NI LabVIEW environment to provide continuous online system monitoring using vibration features, including the real time mode and transient analysis. Blocks of 12600 discrete samples were continuously received at the base unit and analysed, these features were then processed using several algorithms and logged continuously in order to build up the data history. All the analysis, feature extraction, and data logging processes of the vibration features are achieved at the base unit. The validation of the developed monitoring algorithm based on AR approach was successful on small scale mechanical transmissions [30].

5. Testing and Validation of the Automotive Mechanical Transmissions Test Rig and the Smart Vibration Analysis Software

The system validation will comprise a series of tests designed to achieve the proposed aim of developing and validating the behaviour of the smart vibration analysis software including the AR algorithms, and investigating its capability to provide information to users about the system status. All tests were undertaken in such a way as to ensure that failures would develop.
Further publications will follow to provide the results of this series of tests including, for healthy, in-service, and faulty gears that are working in real application such as automotive transmission gear box in which the failure under accelerated conditions were brought about by introducing artificial errors to the gear flanks. All the three testes will be carried out at the same speed and torque until the tests end.

6. Conclusions

The study has presented a new wireless vibration measuring system that was able to detect different conditions of gears in automotive gearbox and clearly identify its condition using only one accelerometer placed on the gearbox casing. The study has focused on monitoring the progression of gear faults in spur and helical gears, using model-based parametric method AR algorithms based on vibration data only. The online information about the transmission condition can provide a solution for PHM systems. The system solved a major problem for application those sensing points are far from acquisition and analysis point. The system is being developed for use on 130mm automotive manual transmissions, but could be adapted for other transmission or machinery systems rotating machinery. Further publications will follow to provide the results of the vibration analysis tool including the AR algorithms.

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