Mechanical Systems and Signal Processing 56-57 (2015) 173–180

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

A technique for the vibration signal analysis in vehicle diagnostics

Andrzej Puchalski *

University of Technology and Humanities in Radom, Institute of Maintenance of Vehicles and Machines, ul. Chrobrego 45, 26-600 Radom, Poland

ARTICLE INFO

Article history:
Received 14 January 2014
Received in revised form
6 November 2014
Accepted 10 November 2014
Available online 26 November 2014

Keywords:
Vibrodiagnostics
Empirical models
Statistical feature vector
Singular value decomposition
Features classification

ABSTRACT

The method of utilising signals of vibration acceleration in the on-line and off-line diagnostics of mechanical defects of internal combustion engines is presented in the paper. The monitored vibration signals of the spark ignition (SI) engine in various maintenance states of the valve system were investigated.

The suggested technique is based on mathematical methods of the lower triangular–orthogonal (LQ) factorisation and the singular value decomposition (SVD) of observation subspaces computed on a vibration time series after their angular resampling without any transformations in the frequency domain. The applied algorithm of data processing filters excessive information and allows the selection of diagnostic features (essential from the maintenance point of view) and generates the empirical model and matrix residuals assessed in the no-fault state as being 'zero'. Then, statistical feature vectors, for which the averaged successive singular values of the residuals of the observation subspaces of the vibration signals were assumed as components, were analysed. As a result of this procedure the vectors of lower dimensions reduced to components, allowing the classification of observations within all defined classes, were obtained. On the basis of these vectors a scalar measure – sensitive to the kind of defect – was proposed and verified.

1. Introduction

Qualifications of engines, machines and on-board devices of vehicles and heavy machinery into no-fault or fault categories on the basis of vibration signals are the consequences of comparing the real state with the one considered as the no-fault [1–3]. This is a process requiring – in the era of mechatronic systems [4] – proper aim defining, data collecting, filtration, normalisation and transformation as well as the selection of essential diagnostic features and decision taking. The applied solutions belong to methods of diagnostics according to models (of processes or signals) [5] and according to observed data [6–8], the realisation of which leads to the generation of residuals of a reliable diagnostic symptom. In the first case the mathematical models of the assumed structure are applied. The simulation diagnostics of technical devices based on their quantitative models can be realised by the estimation of parameters and state vector reconstruction by means of filters [9] (originated from the Kalman filters [10] concept or Luenberger observers), by using the parity relation or signal analysis [11,12]. The measure of the estimation accuracy of the observed signal is the residual calculated in each

* Tel.: +48 48361 7603.
E-mail address: andrzej.puchalski@uthrad.pl

http://dx.doi.org/10.1016/j.ymssp.2014.11.007

algorithm cycle on the basis of the actual signal value and its estimate. The residual value changes when the characteristic of the monitored signal differs from that of the reference signal. An index based on Euclidean norm of the residual vector formed for successive sampling periods, or e.g. on the Mahalanobis norm, which takes into consideration the specificity of the observation vector (represented by the covariance matrix) is applied for the estimation of the state of the object being diagnosed. The second method is based on transformations of subspaces of observations leading to the generation of a system empirical model and statistical residuals estimated in the no-fault state as 'zero'. A detection of residual changes when its probability distribution – in the general case – is not known, which requires assuming statistical local hypothesis. A diagnostics is a consequence of testing the zero hypothesis against the alternative one of using the idea of generalised likelihood ratio (GLR) [13–15]. The null space analysis (NSA) indicates other solutions. In this case, the algorithm of diagnostics generates a residual matrix using the image of the weighted Hankel matrix and the left null space of this matrix, and allows recognising the state of the object on the basis of the index – distance in the residuals space [16].

The filtration in the Kalman model approach as well as the filtration according to statistical properties by stochastic subspace identification methods found numerous applications in on-line and off-line vibroacoustic diagnostics of automotive internal combustion engines and electric motors, of power transmission systems, fuel systems, exhaust gases recycling systems, detection of engine knock and misfire [17–24]. The most popular way of searching for vibrodiagnostic features is based on the frequency analysis and spectral properties of the observed signals. Time–frequency methods such as the short-term Fourier transform, Wigner–Ville distribution, wavelet transform, envelope analysis (Hilbert–Huang transform) or cepstrum analysis are applied in procedures of preparing the parameter base for features selection of signals, for which an assumption of steady state cannot be made. Another approach requires generation of parameters related to the time signal of the acceleration of vibration, such as the absolute value, amplitude, peak-to-peak value, rms value, short time energy, statistical moments and cumulants of the first, second and higher orders. In algorithms of identification of defects on the basis of vibration signal features the tools originated from the principal component analysis (PCA) [25] and classification by means of neural networks of Support Vector Machines (SVM) [26,27], MultiLayer Perceptron (MLP) [28], Counter-Propagation and Self Organising Map (CP&SOM) [29], nearest neighbour classifiers – kNN [30] and Bayesian probabilistic classifiers [31], were applied.

A diagnostics of vehicle systems on the basis of vibration time signals by statistical subspace methods is proposed in the paper. The experimental data originated from time series observations after angular resampling without any filtrations and transformations in the frequency domain was used in the selection procedure of diagnostic features. Orthogonal decompositions of the data Hankel matrix allowed obtaining the observability matrix and the empirical model of the system. This fact was used for a nonparametric way of generating the residual matrices assessed in the no-fault state as 'zero'.

A new way of concluding that a defect occurred is presented. This conclusion was arrived on the basis of bands of the scatter of statistical feature vectors, whose average successive singular values of residuals of the observation subspace, under the given technical state, were assumed as components. The SVD is a tool of numerous methods of the vibrodiagnostics estimation of the technical state of rotating systems [32,33]. Methods based on proper orthogonal decomposition, e.g. principal component analysis (PCA) [34,35] were also used in the proposed – up to the present – solutions of the vibration signals analysis in vehicles. However the features classification, by means of the vector of averaged singular values of the statistical residual matrices generated during the experiment, was not performed.

It should be emphasised that this method allows performing multidimensional statistical vibroanalysis of the valve system state of the SI engine on the basis of data originated from one recording channel, in the environment of several disturbing signals as a result of the presence of various vibration sources.

2. Essence of the applied diagnostic technique

The diagnostic method proposed in this paper assumes that the detection problem of mechanical system defects on the basis of vibration monitoring is equivalent to the analysis of changes in the eigenstructure of its linear state space model with a non-stationary process noise. This approach is the essence of the maintenance modal analysis allowing diagnosis of objects subjected to equilibrium disturbances. The data originated from observations of the instantaneous values of signals of the vibration acceleration of the tested valve systems were resampled in order to equalise the number of samples analysed in each cycle of engine operation. This procedure transformed the observed signal from the time into the angle domain based on the interpolation.

Let the discrete model of such system be described by stochastic equations of state and observation:

$$x_k = Ax_{k-1} + \delta_{k-1}, \tag{1}$$

$$y_k = Cx_k + \varepsilon_k \tag{2}$$

where $x_k \in R^n$is the state vector, $y_k \in R^m$ is the response (observation) vector in the $k$thsampling moment, $A \in R^{nxn}$, $C \in R^{mxn}$, δ_k and ε_k represent white Gaussian noises with the expected values of zero and covariance matrices Q_k and R_k, respectively, taking into account the model uncertainty and observation noises. The matrix pair (A, C) or corresponding to it the system observability matrix $\mathcal{O}_{p+1}$ enables determining the eigenstructure and modal description of the object.