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Multisolution Analysis Time Series Data and RUL Estimate

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The model and algorithm for RUL estimation of the rotating machinery is constructed. RUL estimates are presented analytically. Random walk model of finite segments of the wavelet coefficients of observed signal is considered as the original model. We consider all possible cases in the problems of multi-dimensional random walk vectors free walk, walk with limitations of walk in a multiply connected space. In this case, the problem of RUL estimate is reduced to the assessment of the achievement by the wandering vector the preassigned critical values or areas of critical values. For this the probability of transition from the initial value to some preassigned values is determined using the representation of this probability by the Feynman path integral. During the monitoring of the operation of mechanical block is determined the type of random walk of observable process. After that there is an automatic choice of model for RUL estimates. In some cases it is possible to calculate the Feynman path integral and result analytical formula for RUL estimates. In other cases, after select the type random walk for RUL estimates the solutions of evolution equations for the transition probabilities are studied numerically.
It is shown that for the RUL estimates is needed mode of continuous or periodic monitoring, because the state of the mechanical system can change and therefore the conditions of applicability of the random walk model are changed. In this case, the correction of the calculated estimates is needed. Therefore, the paper discusses the issue about prognosis of changing the conditions of applicability of random walk models. The described algorithm is implemented in PHM computing cluster. For full analysis of life time estimates the cloud computing service is used. The experimental data are shown.

1. Introduction

In PHM models the remaining useful life (RUL) estimates are needed for the effective determination of predicted maintenance strategy. Basic requests of predicted maintenance to the PHM were listed in the report (Hess, 2011) on the PHM conference in Shenzhen. At the same conference and PHM conference in Beijing S. Kirillov et al (2011, 2012) presented the basic model of the prognosis for all failure progression timeline stages. Goal of this paper to further develop RUL estimates based on Feynman path integral calculation and determination of the conditions and monitoring parameters that are necessary to obtain predicted useful life remaining estimates. Under the RUL in this case means the following. RUL is the time required to reach a state in which there clear signs of defects of mechanical rotating equipment. Introduced in the papers by Kirillov and Pecht (2012) the principles of hierarchical ordering of failure signs allow to separate the early signs from the later, hidden from the early signs, etc. on the scale of failure progression timeline. This paper has another purpose, namely development of a model predicted useful life remaining estimates. The principles of hierarchy in the form of degeneration of sign are accounted as the presence various prohibitions at random walk of dimensional process vector defined on the set of wavelet coefficients of the initial observed signal.

2. Model and algorithm

Model of PDF representation for the transition probabilities of vector processes defined on the set of the wavelet coefficients of the observed vibration signal in the form of Feynman path integral is taken as a basis for estimates of RUL, Figure 1.This model is described by Kirillov and Pecht (2012). After the

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procedure of secondary discretization, signal s represent as a vibration signal in an angular variable φ, $S'(\varphi), \varphi \in [0,4\pi]$.
At the next step a signal is represented by a set of finite segments $\{N_{W_{j,k}}\}$ of wavelet coefficients $S'(\varphi)$ as follows. A set of finite segments of wavelet decomposition of vibration signals is

$$\{R_i\} \stackrel{\text{def}}{=} \{N_{iW_{j,k}}: i\,N^* \leq N \leq (i+1)N^*,\ i = 0,1,2,3 \dots\} \quad (1)$$

at fixed scale *j* and translation k, where (*j, k*) - the index of wavelet decomposition coefficients and *N*-number of cycle of engine crankshaft .
The model there are used models constructed on the basis of representation $P(R,i)$ probability of transition for the I steps to the state R in the form of Feynman path integral

$$P(R_0, R_L, L) = \int_{r(0)=R_0}^{r(L)=R_L} D[r(s)]\exp[-\int_0^L ds\langle\xi\rangle_L r_L^2(S)] \quad (2)$$

L - is continuous analog i, in $P(R,i)$; $\langle\xi\rangle$ - is the average value, ΔR_i; $r_L(s)$ **-** is parameterization of polygonal $\{\Delta R_i; i = 1,2,3 \dots\}$.
Representation of the transition probability from one physical state to another by means of Feynman path integral in various physical models developed in the works of the Ziman (1979) and Kleinert (2004). In this paper we use the same approach modified under the high dimensions N^* space of finite segments of the wavelet coefficients. Such representation of the transition probability leads to partial differential equation for $P(R_0, R_L, L)$. The obtained equations allow to calculate the transition probability in an explicit form or calculate moments of the transition probability. The solution of inverse equations for the moments gives values L or discrete values i, that irreversible for transition to the pre-fixed state $\boldsymbol{R}$, which is the basis for RUL estimate
The next steps of models of estimates RUL divided into algorithmic blocks, as shown in Figure 2.
Arriving the set of wavelet coefficients $\{N_{W_{j,k}}; N = 1,2,3 \dots\}$ of signal $S(\varphi)$ subjected to further processing in the block B in order to accurate estimates of RUL at the stage B (Early incipient fault to Component or Subsystem Failure), ie, estimates of RUL (B), for this:
1. in the block **B1** , Fig.2 the set of wavelet coefficients $\{N_{W_{j,k}}; N = 1,2,3 \dots\}$ of signal $S(\varphi)$ is transformed into a set of finite segments of the wavelet coefficients multidimensional vectors of state of the system $R \in R^{N^*}$ with a certain fixed dimension N^*.
The value N^* is definite by formula

$$N^* = \min_N(|PDF(N) - PDF(N-1)| < \varepsilon) \quad (3)$$

with a predetermined value ε, defined by taking into account the accuracy of the measuring sensors and digital electronics.
2. on a set of sequential finite segments is determined by process

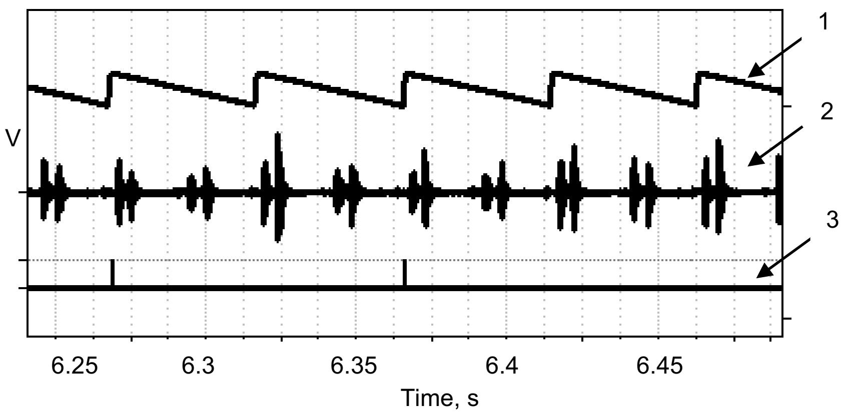

Figure 1: 1 - crankshaft rotation angle sensor (CRAS) signal φ, 2 - vibration signal s, 3- mark signal for first cylinder

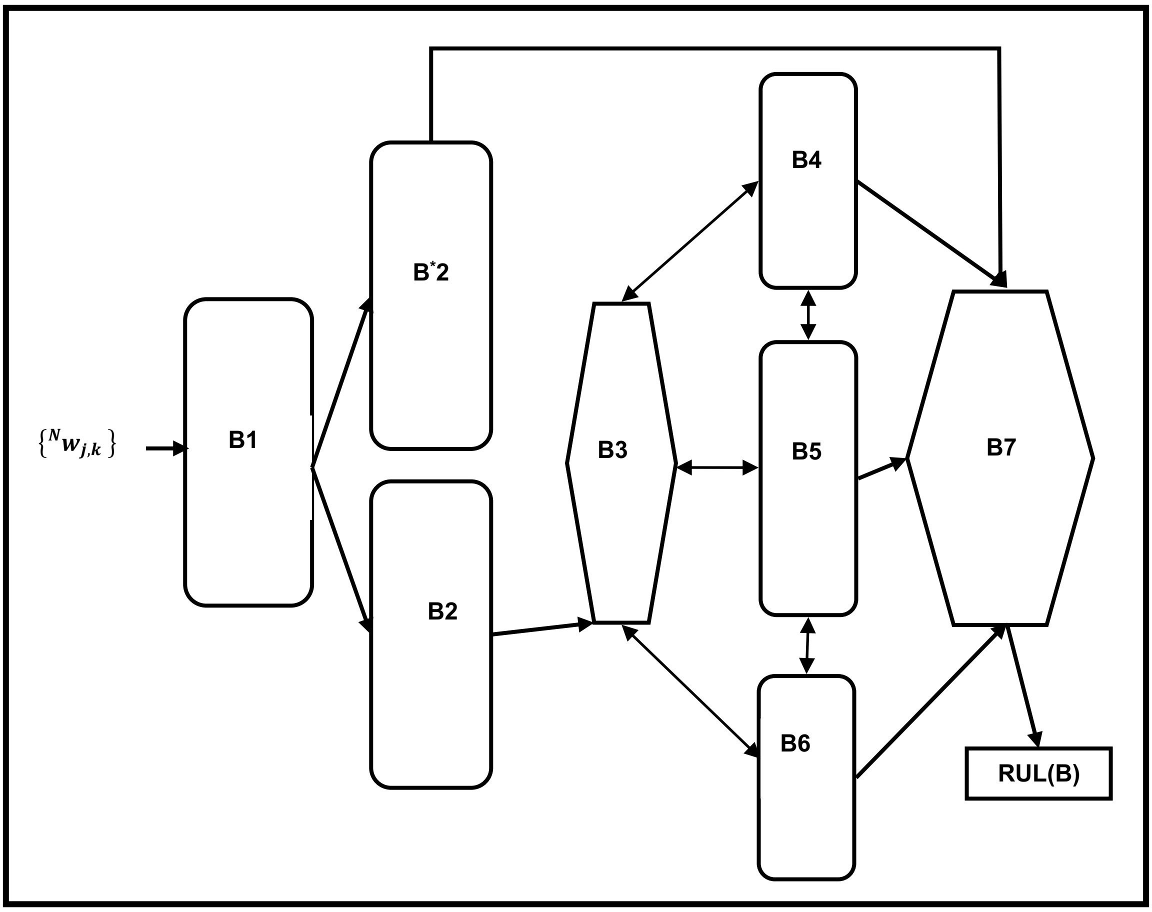

Figure 2: the block diagram of algorithms for calculating RUL

$\Delta\boldsymbol{R}_i = \boldsymbol{R}_i - \boldsymbol{R}_{i-1}$

Then a set $\{\Delta\boldsymbol{R}_i; \mathrm{i} = 1,2,3 \ldots\}$ is transmitted to the block B2 for further processing.
As a result the process of random walk vector $\Delta\boldsymbol{R}_i$ in N^*- dimensional space is considered and the problem of prognosis and assessment of RUL(B) at the stage **B**, transition (early incipient fault to component or subsystem failure) is reduces to calculating the number of steps i, for which the state vector $\boldsymbol{R}$ gets from the original (etalon) state in the region I (component or subsystem failure) with probability $P(\boldsymbol{R}, i)$.
In parallel, the coefficients $\{{}^{N}w_{j,k}; N = 1,2,3 \ldots\}$ of signal $S(\varphi)$ and the stationary distribution function $PDF_{j,k}(N^*)$ are transmitted to block B2* for prognosis of sudden fast catastrophic failure.
In block B2* is made analysis of the stationary distribution function from the standpoint of catastrophe theory
In the block B2 the set $\{\Delta\boldsymbol{R}_i; \mathrm{i} = 1,2,3 \ldots\}$ subjected to further processing in order to determine its statistical properties.
1. The multidimensional empirical distribution function $PDF(\Delta\boldsymbol{R}_i)$ is constructed
2. The empirical moments of the distribution function are calculated;
3. cross-correlation function for the process $\Delta\boldsymbol{R}_i$ is calculated.
Further defined above quantities and the set $\{\Delta\boldsymbol{R}_i; \mathrm{i} = 1,2,3 \ldots\}$ are transmitted to the block B3 for further processing.
Task of the block B3 is on the basis of data received from block B2 to determine the character of random walk of multidimensional vector.
For this coming to the block B3 sets $\{\Delta\boldsymbol{R}_i; \mathrm{i} = 1,2,3 \ldots\}$ and their defined in the block B2 statistical characteristics are compared on basis of etalon methods of statistical testing of hypotheses (zero hypotheses) with the corresponding distribution functions and the statistical characteristics of listed below models:
1. Models of the free random walk.
2. Models of random walk with constraints.

3. Models of random walk in a non-simply-connected domain.
After choosing one of the models (1-3) based on the statistical assessment of the hypotheses $\{\Delta\boldsymbol{R}_i; \mathrm{i} = 1,2,3 \dots\}$ and their statistical characteristics defined in the block B2, and also the values $\langle\xi\rangle$ и $\boldsymbol{r}_L\ (\boldsymbol{s})$ are transmitted depending on the results of the statistical hypothesis testing to blocks:
B4 - under condition of confirmation of a hypothesis of model of the free random walk (1);
B5 - under condition of confirmation of a hypothesis of model of random walk with constraints (2);
B6 - under condition of confirmation of a hypothesis of model of random walk in a non-simply-connected domain (3).
Blocks B4, B5, B6 are intended for assessment of RUL (B) depending on fulfillment of the conditions 1-3.
Calculation of RUL (B) on basis of analytical expressions is presented in the form of Feynman path integral.
Calculation of RUL (B) on basis of analytical expressions of the moments of the distribution function is presented in the form of Feynman path integral.
Calculation of RUL (B) on basis of analytical or numerical solutions of kinetic equations, determined from the representation of the distribution function in the form of Feynman path integral.
At change of character of random walk, control is transferred to the block B3, where the model selection is carried out again. Then data are transmitted to the corresponding block B4, B5, B6 for the correction of RUL:
Under condition of confirmation of a hypothesis of model of the free random walk (1):
1. To the block B4 the value $\{\Delta\boldsymbol{R}_i; \mathrm{i} = 1,2,3 \dots\}$ and $\langle\xi\rangle$- the average value $\Delta\boldsymbol{R}_i$ are transmitted for calculation

$$L = \frac{<\|\boldsymbol{R}\|^2>^2}{(N^*-1)\langle\xi\rangle} \tag{4}$$

L – is the number of revolutions required to achieve the state vector $\boldsymbol{R}$ with root-mean-square norm $< \|\boldsymbol{R}\|^2 >$
2. the next step is a comparison of value L, calculated by the formula (2) and the empirical value L, obtained from rotation sensor, and assessment of root-mean-square deviation $< \|\boldsymbol{R}\|^2 >$, obtained on the basis of empirical values $\boldsymbol{R}_L$.;
3. at coincidence of model and empirical estimates L , RUL(B) is determined by the formula

$$RUL(B) = \frac{<\|\boldsymbol{R}^C\|^2>^2}{(N^*-1)\langle\xi\rangle} \tag{5}$$

$\boldsymbol{R}^C$ **-** belongs to the boundary of transition II – I (I. component or subsystem failure).
Under condition of confirmation of a hypothesis of model of random walk with constraints (2) to the block B5 the value $\{\Delta\boldsymbol{R}_i; \mathrm{i} = 1,2,3 \dots\}$ and $\langle\xi\rangle$- the average value $\Delta\boldsymbol{R}_i$ are transmitted for calculation L on basis of formula (4)

$$< \|\boldsymbol{R}\|^2 >= 2\left\{\Theta L - \Theta^2\left[1 - e^{-L/\Theta}\right]\right\} \tag{6}$$

where

$$\Theta = \frac{const}{\langle\xi\rangle(N^* - 1)}$$

1. the next step is a comparison of value L, calculated by the formula (4) and the empirical value L, obtained from rotation sensor, and assessment of root-mean-square deviation $< \|\boldsymbol{R}\|^2 >$, obtained on the basis of empirical values $\boldsymbol{R}_L$.;
2. at coincidence of model and empirical estimates L , RUL(B) is determined by the formula

$$< \|\boldsymbol{R}^c\|^2 >= 2\left\{\Theta \mathrm{RUL(B)} - \Theta^2\left[1 - e^{-\mathrm{RUL(B)}/\Theta}\right]\right\} \tag{7}$$

B6 Under condition of confirmation of a hypothesis of model of random walk in a non-simply-connected domain (3) to the block B5 the value $\{\Delta\boldsymbol{R}_i; \mathrm{i} = 1,2,3 \dots\}$ and $\langle\xi\rangle$- the average value $\Delta\boldsymbol{R}_i$ are transmitted for calculation L on basis of Eq. (7)

$$< \|\boldsymbol{R}\ \|^2 >= \langle\xi\rangle^{1/(N^*+2)}\left(\frac{N^*+2}{3}\sqrt{\frac{2\langle\xi\rangle}{N^*}}L\right)^{6/N^*+2} \tag{8}$$

1. the next step is a comparison of value L, calculated by the formula (6) and the empirical value L, obtained from rotation sensor, and assessment of root-mean-square deviation $< \|\boldsymbol{R}\|^2 >$, obtained on the basis of empirical values $\boldsymbol{R}_L$.;
2. at coincidence of model and empirical estimates L , RUL(B) is determined as solution of equation (8)

$$< \|\boldsymbol{R}^c\|^2 >= \langle\xi\rangle^{1/(N^*+2)} \left(\frac{N^*+2}{3}\sqrt{\frac{2\langle\xi\rangle}{N^*}}\mathrm{RUL(B)}\right)^{6/N^*+2} \quad (9)$$

Then the set of finite segments (state vectors) $\{\Delta\boldsymbol{R}_i; \mathrm{i} = 1,2,3 \dots\}$ is transmitted to the block B7 for the further processing.

Block B7 is intended for the formation of text-graphic messages based on the results of processing of processes in the block B2* and processing of exception of calculation results in block B4, B5, B6.

3. Experiment results

Diesel engines of trucks, which being in continuous operation, have been subjected to long-term monitoring. In monitoring the vibration sensor signals of engine body in a neighborhood of block of cylinders have been registered. The purpose of monitoring is to confirm or deny the algorithms described above for determining RUL. Experimental values of the vector processes formed from wavelet coefficients of the vibration sensor signal and the number of motor shaft rotations have been measured in the condition of periodic monitoring. In this case, the same type engines have been chosen with a different duration of operation, divided into three groups according to the duration of operation: a short period of operation, the average period, a long period of operation.
The experimental values of dispersion of the Euclidean norm of sets of segments of wavelet decomposition coefficient are shown on Figure 3.The squares is the engines of a small operation period up to 2 years, triangles - the average period, point - a long period of operation. The theoretical curves for the dispersion, calculated on the basis of Feynman integral in the three considered cases of the algorithm approximate the experimental data by method of variation of the free parameters N^* and "*const*". Since the N^* parameter is defined by the inequality (3) ambiguous, it is also varied for the purpose of best approximation.
The presented data support the validity of the estimates RUL by formulas (5, 7, 9).

4. Conclusion

Thus, the model and algorithms of RUL estimate based on the representation of the trajectories of vector stochastic processes as a random walk of multidimensional stochastic process. In the representation of numbers of rotation mechanism cycle as a discrete time and then moves to the continuous representation of PDF of multidimensional process is defined in the representation of its Feynman path integral.

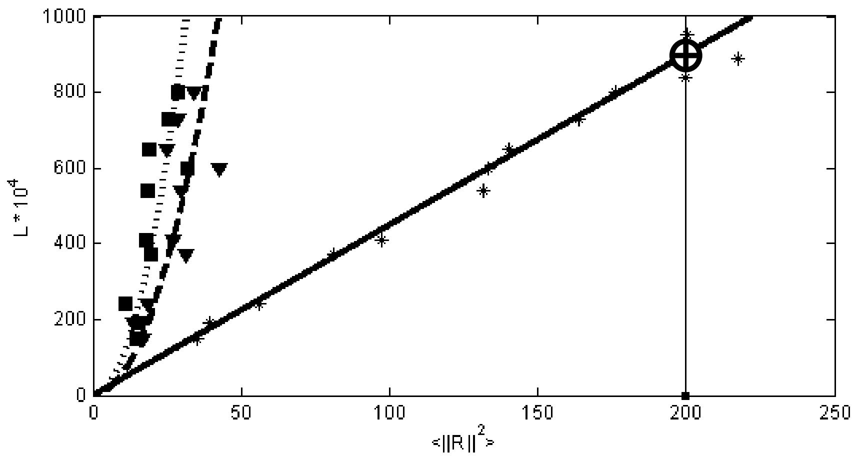

Figure 3: the theoretical L as a function of $< \|\boldsymbol{R}\|^2 >$) graphs and their experimental values; $\oplus$- component or subsystem failure.

Such representation gives an opportunity to obtain the evolution equation for the PDF of the transition probabilities to different vectors with the permissible values of its components, thereby to determine the evolution of the PDF. Or to obtain both on the basis of evolution equations, and by direct calculation of Feynman integral. For large computational complexity on the basis of Feynman integral can be computed only some characteristics of the PDF, in particular, moments or cumulants. In any case, the obtained values are immediate prognosis for failures, if failures or dysfunctions are defined by specific subsets of the multidimensional space of vectors. These subsets are determined by the forbidden condition.

The physical nature of the forbidden condition is very diverse. However, they should clearly define whether a particular vector condition belongs to forbidden or not. As the topology and the boundaries separating the forbidden sets of values from permitted are very complex, for example boundaries can have a fractal structure, structure of an implicit set, to be multiply connected, stratified etc. Condition of constancy of one - dimensional PDF generates in multidimensional space, being addition to orbits, the permutation group.

So the introduction of the conservation principle of the one-dimensional PDF generates (forbidden principle) hierarchical model by introducing the chronological ordering on the set of all possible signs. Investigation of stochastic properties of a multidimensional process allows to determine the evolution equations of the process, and thereby to answer the question about the time of the achievements of the forbidden subsets, i.e. determine RUL.

Further research in this area is now aimed at the solution of the problem. As a first approximation it is assumed that the forbidden set have no impact on evolution of the process, and it is only necessary to calculate the time to achieve the forbidden set by the state vector. However, the detailed study it was found that the forbidden rules can influence the evolution of the system, changing the estimation of the first approximation. For example, the principle of the invariance of the multidimensional PDF for transition probabilities eventually leads to the processes on smooth manifolds, presented as a homogeneous space of groups of motions of Euclidean metric, or degeneration spaces. At the same time method of representation of the transition probabilities in the form of Feynman path integral is transferred to the degeneracy space, having, as a rule, non-trivial homotopy type. In physics, this transition is equivalent to the introduction of a interaction potential. That is forbidden sets in a more general approach influence the evolution of itself multi-dimensional process. Thus the value of RUL is corrected.

It is also necessary to note that the transition to a process consisting of a finite segment of wavelet coefficients requires significant computational resources in further calculations, for example, in the form of cloud calculation service. This requirement in many respects determines the entire architecture of PHM system for preventive prognosis. Finally, representation of the transition probabilities in the form of Feynman path integral is the basis for the development of predictive failure machines in real time mode for vector processes. In particular, on this basis are constructed recursively multilayer neural network. In the one dimensional case, an example of such networks is presented in the paper Zio et al. (2012)

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