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Remote Calculating PHM Cluster: the First Results

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The work describes the computing cluster for early fault prognosis and estimates of RUL for technical objects: wind turbines, internal combustion engines, gas turbine, etc.
Basic functions of the cluster, consisting of the algorithms are described:
- Preventive smart monitoring to detect signs of failure;
- Definition of computing models of the time evolution of features and accurate RUL estimate;
- Analysis of telemetry data in order to detecting and further monitoring of the hidden signs which give early prognosis (preventive prognosis) of potential risks of failure in the absence of statistical characteristics;
- Learning of recognizing automata (HMM, neural networks) for real-time autonomous systems of smart preventive monitoring.
The computational algorithms are based on models that combine the methods of the theory of dynamical systems, the theory of stochastic processes, statistical physics and field theory.
The organization of algorithms in the hierarchical structure based on the principles of degeneration of failure signs helped identify more early signs of failure.
This, in turn, allows to calculate effective Predictive maintenance strategies.
The first experimental results of the cluster operation are shown. In particular, it is show that the hierarchical approach to the RUL prognosis has the structure of one-dimensional graph.
The experiment confirmed the need to integrate remote computing cluster with peripheral recognizing automata in a united network for effective organization of automata operation and their retraining.

Introduction

Development of methods and algorithms for remote PHM systems have been taken by the united team CALCE (USA), SmartSys Prognosis (space and telecommunication technological cluster, Skolkovo, Moscow), SmartSys Prognosis Inc. (USA) in recent years. The project objectives have concentrated on creating and market approbation of remote PHM system in order to determine the necessary functionality, architecture and basic scenarios. A pilot remote PHM system supported by a parallel computing resource as a service of cloud computing, supercomputers and grid systems - the remote computing cluster PHM has been developed. The basic attention was given to construction of effective schemes of PHM monitoring, development and testing of basic prognosis models and their classification based on the characteristics of the stochastic properties of the observed signal. This takes into account the following factors of monitoring objects:

1. Availability of traditional diagnostic and control systems on the monitoring objects (on-board diagnostic system);
2. Availability of computing resources in on-board diagnostic system, in mobile devices and gadgets, navigation systems, etc, as well as the possibility of remote downloading of computing applications for this mobile platform;
3. Availability of opportunities of telemetric data transmission to the remote PHM cluster.

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Some results of testing PHM prognosis models for internal combustion engines were presented at the SAE World Congress in Detroit (2011a). Basic mathematical models and algorithms were discussed at PHM conferences in Shenzhen (2011b) and Beijing (2012). In particular, the authors have described methods of signal processing and the complex hierarchical prognosis model (CH & P) and its algorithms. The present work is devoted to describing the general structure of remote computing cluster, the description of models and algorithms, useful first results of the pilot version of the cluster, the discussion of problems and future prospects for the development of the remote cluster.

1. Model

The basis of computational algorithms of PHM cluster is complex hierarchical prognosis model CH & P, for the first time stated in paper and the report Kirillov et al. (2012). As an example, in the papers the authors consider internal combustion engine failures, revealed based on analysis of vibration engine body or certain mechanical car and track parts: gearbox and transmission, bearings, brakes, and so on. In view of the generality of CH & P prognosis model, its methods also spread to all technical objects of high complexity: generators, wind generators, turbines, etc Thus, these models are necessary for the organization of combustion control and safety assessment and risk analysis in the aerospace industry, for example, in satellite engines. This issue are considered in the paper Razionale et al. (2012) Recently, these methods are adapted to PHM applications in medicine, in particular, on expansion of prognostic capability of Holter heart rate monitoring systems.

Methods of diagnosis as well as prognosis methods are based on the identification of failure sings, failures detection and determination of time or speed development of signs. For example, in the diagnosis of rotating equipment statistical characteristics of the vibration signal, peak factor, Kurtosis factor, etc. are signs of failures.

However, the following questions concerning essence of PHM methods are relevant:

- How to describe the time evolution of failure signs? This question is equivalent to estimate of RUL.
- Whether the set of signs is full, i.e. whether other signs exist? And in this question it is necessary to prove or that other signs do not exist, or to show full system of signs.
- Is there some kind of order on the set of signs of failure how and what principles determine early signs from later?

Cited here research and the results of the pilot version show that set of failure signs derived from the observed signal of sensors has a hierarchical structure as shown on Figure 1.

The hierarchical structure of set of failure signs is the basis of CH & P model and reflects the qualitative change of trajectories of some very complex and chaotic dynamical system describing the process of the functioning of mechanism. In most cases, the explicit form of the system is unknown for reasons of complexity and the impossibility to control all of its variables.

The following principles reflect the hierarchical structure of set of failure signs and are the basis for constructing CH & P model.

1.1 The first level

The first level corresponds to the transition (I-0), Fig1 and is determined by a probability distribution function of the observed value of PDF or set of PDF wavelet coefficients of the observed value at each fixed time or rotation angle of the shaft of rotational mechanism. Signs of failures are characterized by numerical values of the moments of PDF, and their rational expressions Kurtosis factor, Hurst index, etc. Prognosis and estimate of RUL on this level is reduced to calculating time of reaching of the boundaries of states by the system (0) on Figure1. As a model for determining the evolution equations is used in calculating the RUL vector model of random walks of the finite segments of wavelet coefficients of the observed signal and the representation of the probability distribution function of the transition on the set of valid values of segments in the form of Feynman integrals. In this case, the evolution equations are defined in the form of the Fokker - Planck equation, the Schrodinger equation, the diffusion equation, etc. with further transition to the equations of moments. Methods for obtaining evolution equations are presented by the authors, also by Kleinert (2004), etc.

1.2 The second level

The next level is split into two sub-levels, transitions (II-I, III-I), each of which is defined as follows:

The level (II-I,III-I) appears in the case when the process becomes stationary with discrete time or its continuous variant. In this case, all of the previous signs are degenerate because does not change at mechanism operation, therefore, the time evolution of and all the characteristics in the form of combinations of moments PDF are absent.

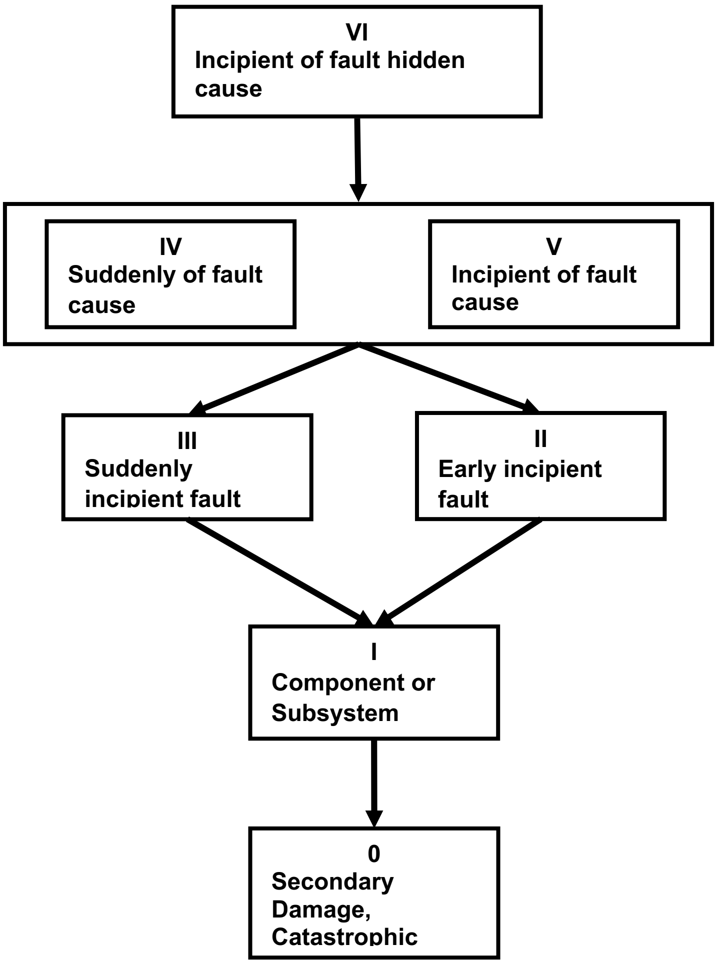

Figure.1: failure progression timeline

The transition to the vector process on the level (II-I) on Figure 1 with subsequent presentation of probability of the transition function as a Feynman integral also leads to evolution equations, but under the condition that probability distribution function (PDF) is preserved. This condition very complicates model, however, this complication makes the RUL estimate as a time of the transition from the border (II) to the border (I) of more accurate.

Sub-level (III-I) is introduced to account for the following circumstances. Under condition of preservation the fast of PDF changes in PDF, characterized by a sudden transition from one stationary PDF to the other stationary PDF, for example, the transition from single-modal PDF to bimodal, etc. are possible. These processes are simulated on the basis of the bifurcation theory and catastrophe theory. The formalized mathematical model of the catastrophe theory is contained in Arnold et al. (1982). In this case, monitoring of PDF parameters, which in the process of slow evolution can get in the neighborhood of the bifurcation set is needed. The waveform of PDF quickly is reconstructed into another. In the simplest case it is enough to determine only two parameters of polynomial approximation of the PDF. For assessing RUL it is necessary represent the coefficients of polynomial approximation in the form of sequence of random variables. The theoretical part of the catastrophe model is developed by the authors based on the theory of noise-induced transitions of Lefever (1984).

1.3 The third level

The next level and the corresponding signs are realized when the random walk of segment happens in the admissible domain, and the PDF of the transition probabilities do not depend on time.

In the cited here works of the authors at this level, estimates and prognosis were limited to estimates of Kolmogorov complexity. More detailed analysis of the results of the pilot version of PHM cluster showed that this level is split into two sublevels. Both sub-levels are characterized by of the stationary of transition probabilities. Sublevel of transitions (IV, V – III, II), as the sub-layer (III – I), corresponds to fast transitions with the change of PDF probabilities of transitions between different stationary PDF probabilities of transitions. As well as in the previous case, catastrophe theory is used here as a model that evaluates the RUL. Sublevel of transitions (V – III, II) defined as a transition to the boundary (II,I), defined as a transition to the boundary from which the time evolution of the PDF of the transition probabilities or following stepwise changes begin (III, II – I).

RUL prognosis and estimate at this stage is reduced to the estimates Kolmogorov complexity, relative Kolmogorov complexity of all time series of vector processes defined by the wavelet coefficients of the observed signal. Details of the Kolmogorov complexity at the level (V) presented in the paper of S. Kirillov and et al. (2011) in Harbin.

And finally, the earliest level of the prognosis defined for today in the framework of CH&P models is determined by the transition from vector processes to processes on the orbits of the degeneracy groups of the previous level. As an example, a model of random walk in the degeneracy space of PDF transition probabilities of Gaussian type is considered. In this case, the primary time series of data of wavelet coefficients of the observed signal convert taking pairwise differences and projections on the degeneracy space, K-decomposition.

1.4 The fourth level

Further analysis uses a model of symbolic dynamics, topological dynamics described in the works (the theory of entropy, symbolic dynamics). Well as theory of Feynman path integral on smooth manifolds is used. It should be noted that the level of D is indicated only by the authors. Strong reasons to consider the transition to the processes on the degeneracy spaces as the system of the new class of levels splittable into multiple sub-levels have appeared now. The transition to stochastic processes on the degeneration space of the PDF for the transition probabilities, in particular, on homogeneous spaces of degeneration space of PDF enters into the PHM practice so-called no amplitude signs.

No amplitude signs or points on the degeneration space characterize existing regularity no amplitude nature in the observed signal or its wavelet coefficients. Representation of the transition probabilities in the form of Feynman path integral, transferred to degeneracy space, allows to calculate the RUL, i.e. the time required to achieve the boundaries of the critical condition in which changes of regularities take place in the observed signal. Change of regularities are expressed in terms Kolmogorov complexity and are evaluated using the entropy and fractal characteristics of the observed signal.

2. PHM cluster architecture and functional basic function

Architecture of pilot cluster represents traditional. Telemetry of the technical object is processed on a remote computer cluster and then in the form of messages delivered to the user. As shown in Figure 2, “A” – is cloud computing service and/or a supercomputer with programs of the analysis by the preventive diagnostic methods;” B” - is set of car and truck with the additional device supporting the vibration sensor and rotation sensor, integrated into the engine or in the form of the device of the independent control; “C” - are service centers with devices based on the engine analyzer, adapted to the measurement of vibration. Remote computing PHM cluster has the learning function of recognizing automata. Modern technical facilities are usually equipped systems of on - board diagnostics.

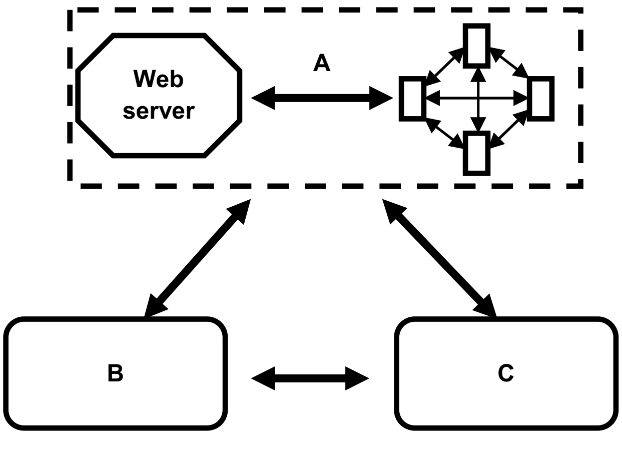

Figure 2: preventive monitoring scheme

These systems have small computing resources. Besides computational resource have different mobile gadgets as tablet computers, Smartphones, iPhones, etc. Systems of on-board diagnostics supporting Bluetooth protocols or Wi-Fi extend their computing resources by the aforementioned mobile gadgets. This resource should be used for off line modes of monitoring in real time. All together allows to place on such a mobile computing resource the recognizing automata as neural networks, hidden Markov chains, Wiener nonlinear chains, etc.

Recognizing automata so can support remote PHM system of preventive monitoring and work in real time. There are problems to the implementation of on-board recognizing automata.

There are at least two problems.

The first problem is in the implementation of several types of automata in one small computing resource. The presence of hierarchical properties confirms this problem, like the difficult estimate of RUL containing several components. From these facts it follows that recognizing automata are needed to retrain at achievement of boundary of hierarchy level by system Therefore, a variant in which the peripheral automata and remote cluster integrated in one system is seen most effective. In this case the problem of retraining is solved. Solution of this problem is demonstrated by the following example: multi-layer neural network with several pre-determined types of connections and their weights. The network works in a mode of sequential switching from one architecture of connections to another. Type of connection is changed depending on the changes in the characteristics of the stochastic signal in accordance the hierarchy.

The second and more difficult problem is the problem of learning the neural network because multi-layer neural network should process the finite segments of the wavelet coefficient of very large dimension (more than 1000). Classical methods of learning for such dimensions are not working. It is very difficult to collect the necessary number of vectors for neural network learning. Besides often enough especially at the levels (III, V, VI) hidden signs have individual character that makes the problem of learning intractable. In the pilot realization of PHM cluster the problem of learning of recognizing automata was solved as follows. For learning on different levels of the hierarchical model in accordance with Failure Process Hierarchy was used representation of the transition functions as Feynman integrals in multidimensional Euclidean space or on the corresponding space of degeneracy.

Using the approach, originating from the representation of the Heisenberg quantum mechanics, the corresponding representation of the evolution of the system locally linearly is approximated on the whole time axis. Representation of local linear approximation in the form of multilayer neural network removes the problem of neural network learning because connections and weights were placed in accordance with the linear approximation. In addition the problem of retraining of neural network in Failure Process Hierarchy was solved.

Problem of primary learning of recognizing automata at the expense of set of statistics on a remote server and identifying specific levels of hierarchy is also solved. Defining the level of the hierarchy equivalent to the choice of a mathematical model in which learning of recognizing automata is greatly simplified. This simplification allows to consider recognizing automata like local linear approximation of the CH & P models.

3. First results

Results obtained for today should be divided into two families. For the first family should be attributed experimental confirmation of the basic principles of the hierarchical models. Experimental estimate of RUL at all stages of overt and covert signs of failure means here. Basically, subject is estimation of RUL at the stages B, C and D. In this part of experimental testing the encouraging results are obtained in estimates of internal combustion engine failures. These results were presented in the reports on the SAE Congress in Detroit, on PHM conferences in Shenzhen and Beijing. From them it follows that the estimate of RUL on the basis of the evolution of the entropy estimates of Kolmogorov complexity pretend to early prognostic estimates.

However, more long-term monitoring is required to fully confirm the validity of the model. In view of the universality of the model it is necessary to extend the classes of monitoring facilities, including all the types of rotating equipment. At the same monitoring of facilities must be a long time until it is fully wear or repair. Therefore, the remote computer cluster must be part of all existing monitoring systems of technical objects. In addition, the cluster must necessarily support the on-board diagnostics. On the one hand, it is necessary to continue the testing of computational models for their further development. On the other hand, the confirmed results of PHM models, including the CH & P models, for today is enough to make a more effective preventive strategy of prevention, as well as technologies to support recycling, etc.

It is worth noting the following important steps in the development of future computing cluster and PHM applications. As the complexity of the concept of RUL and the whole structure of the hierarchical model and the first results allow to identify the main strategic directions for the further development of PHM applications. In the end it turned out that to implement PHM applications it is necessary to combine remote computing cluster with a large computing resource and peripheral recognizing on-board automata in a single whole with the feedback function for the initial learning and retraining. Demonstrated complexity of the hierarchical models suggest that an effective works of PHM system a permanent or event or periodic monitoring is needed from the beginning of operation of the mechanism, the turbine engine. In this case, the implementation of PHM system, more precisely its effectiveness, will increase in proportion to the volume of monitored similar mechanisms.

It is necessary as especially to note the high complexity of mathematical models which are looked through at work with hierarchical models. That is, any model is an approximation of some typical situations in the state and dynamics of the mechanism. Approximation of the first approach is presented by hierarchical model. Meanwhile, the first results show the existence of more complex configuration of the hierarchy and with a large number of hierarchical and parallel levels. The complexity of the mechanisms, especially gas turbines and internal combustion engines, where the mechanical processes combine with the processes of gas-liquid transfer and turbulent combustion, to it obliges. That is, with the development of combustion models and detailed models of the dynamics of hetero-phase medium the effectiveness of PHM applications will deepen and develop.

Some perspectives for the existence individual signs for each mechanism are seen as well, especially for the earliest signs and all the higher levels of the hierarchy. In the context of the above, the use of universal recognizing automata will not be as effective, and there is a problem of training and retraining of peripheral automata based on an individual chronological database. Finally, in view of the huge variety of mechanisms of high complexity, and with the understanding of the fact that a variety of mechanisms and their types generates such same the variety of hierarchical systems, adapted to specific mechanisms, a more unified approach to the problems of development and commercialization of PHM applications is necessary. It is already clear that other form of interaction between different PHM groups is needed. Concrete step to this interaction is the use of PHM computing cluster in the application to various objects of mechanics and electronics. Therefore, for PHM groups the free use of cluster and public dissemination of the results for creating unified database of chronological database is offered.

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