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Condition monitoring of planetary gearbox by hardware implementation of artificial neural networks

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A B S T R A C T

The hazards of planetary gearboxes' failures are the most crucial in the machinery which directly influence human safety like aircrafts. But also in an industry their damages can cause the large economic losses. Planetary gearboxes are used in wind turbines which operate in non-stationary conditions and are exposed to extreme events. Also bucket-wheel excavators are equipped with high-power gearboxes that are exposed to shocks. Continuous monitoring of their condition is crucial in view of early failures, and to ensure safety of exploitation. Artificial neural networks allow for a quick and effective association of the symptoms with the condition of the machine. Extensive research shows that neural networks can be successfully used to recognize gearboxes' failures; they allow for detection of new failures which were not known at the time of training and can be applied for identification of failures in variable-speed applications. In a majority of the studies conducted so far neural networks were implemented in the software, but for dedicated engineering applications the hardware implementation is being used increasingly, due to high efficiency, flexibility and resistant to harsh environmental conditions. In this paper, a hardware implementation of an artificial neural network designed for condition monitoring of a planetary gearbox is presented. The implementation was done on a Field Programmable Gate Array (FPGA). It is characterized by much higher efficiency and stability than the software one. To assess condition of a gearbox working in non-stationary conditions and for chosen failure modes, a signal pre-processing algorithm based on filtration and estimation of statistics from the vibration signal was used. Additionally, the rewards-punishments training process was improved for a selected neural network, which is based on a Learning Vector Quantization (LVQ) algorithm. Presented classifier can be used as an independent diagnostic system or can be combined with traditional data acquisition systems using FPGAs.

1. Introduction

Continuous monitoring and assessment of the gearboxes' condition is crucial, especially in an industry where the costs of unplanned downtimes outweigh the costs of repairs; also, early prediction of failures ensures safety of exploitation. Gearboxes are used in a majority of mechanical power transmission systems, especially planetary gearboxes are used e.g. in aircrafts, wind turbines, mining and automotive industry. They usually consist of one up to three planetary stages, or combination of planetary and parallel fixed axis stages. This design provides compactness of construction with high power ratio. The failures of planetary gearboxes are the most crucial in the machinery which directly influence human safety. In the aircrafts according to [1,2] the most of the failures in gearboxes occur due to application errors, from which the most common is misalignment. Gearbox failures in wind turbines do not bring so serious safety issues but they can cause big economic losses in case of serious damages. Currently, gearbox related failures are responsible for over 20% downtime of the wind turbines and need replacement after 6–8 years [3,4]. Real-time condition monitoring of components in high power drivetrains can prevent of serious failures of a gearbox, if emergency shutdown is conducted soon enough. This require robust and resistant to harsh environment diagnostic systems. Due to these facts, reliable condition monitoring systems are needed to detect damages at an early stage of development. Many types of defects of gearboxes components (gears, bearings and shafts) are characterized by a specific signature in the residual signal [5–7], which allows to assess their condition. In practice, usually the vibration signals and temperature of the lubricants are analyzed. Since machines operating in non-stationary conditions it is necessary to monitor their operating parameters, such as rotational speed and loading.

Neural classifiers have wide applications in Condition Monitoring (CM), they allow for efficient and effective association

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of symptoms with the condition of the object [8–10]. Applying classifiers based on neural networks allows to identify failures, where a categorization of symptoms using mathematical formulas is ambiguous. Recently, extensive research on the application of neural classifiers in technical diagnostics is carried out [9,11–13]. Artificial Neural Networks (ANNs) are a promising alternative to conventional methods of classification. The ANNs enable transformation of a multi-dimensional space of symptoms into the classes related to condition of an examined object [5]. A local or global transformation of the multi-dimensional space can be extremely difficult by means of mathematical formulas. The ANNs also have an auto-association feature, i.e. they allow associating an image with a pre-remembered pattern [14]. The application of neural networks in technical diagnostics has been presented by Adamczyk et al. in [15], where the Learning Vector Quantization (LVQ) algorithm was applied for failure identification of the machinery operating in non-stationary conditions. A wide study conducted by Czech at al. indicated that neural networks can be successfully used for recognition of gearbox failures. In [16] has been shown that artificial neuron networks, by using data obtained from a model and a real gearbox, offer the highest accuracy of classification. The research was focused on the identification of the tooth failure, and its level of progress. The neural classifiers can be used in detection of the early stages of gears failures, as has been shown in [17]. The author has presented in [18] the application of a probabilistic neural network for detecting the degree of crack development in the tooth root. Dybała et al. have proposed a way of applying the Counter Propagation (CP) neural network in fault detection [19]. In their work, the feature selection method was based on the observation space. The same authors have stated in [20] that "the attractiveness of using artificial neural networks in technical diagnosis consists in the possibility of application of these networks without actually having any knowledge about the mathematical model of the diagnosed object". Barszcz has presented an approach of defects classification for rotating machines based on NARX networks [21]. This method allows to take into account the nonlinearities in the system. The advantage of this method is the possibility of detecting new failures, which were not known at the time of training. In another article [9], the fuzzy-ART neural network has been proposed as a classification system. The introduced normalization procedure has improved the classification process, which was confirmed in the experiment. In the research [22], the problem of selecting training data for neural network in condition monitoring has been raised. In this study, the factors which have an influence on the vibration generated by machines, such as: design, technological and operational parameters were discussed. In another paper [10] the diagnostics of ball bearings by means of ANNs has been presented. In the study, it has been proven that artificial neural networks can be applied for identifying the technical state of the ball bearing in variable-speed applications. Wang et al. [23] have showed the possibility of application of a new integrated classifier for different gearbox with implementation for real-time conditions. In the paper [24] a new multidimensional hybrid intelligent diagnosis method has been proposed. The classifiers were based on a multi-layer perceptron, radial basis function neural network, and K-nearest neighbor classification algorithm. Rafiee et al. [11] in their study have presented a multi-layer perceptron for identification of gears and bearings failures. The application of a neural network based on the self-organizing feature map for gear faults identification has been presented by Chebg et al. [13]. The authors applied Hilbert–Huang transform for features extraction from vibration signal generated by gears. The other researches in [8] have presented possibility of extracting of gear fault features from vibration signals by the ensemble empirical mode decomposition method, and application of ANN classifier for the purpose of diagnosing.

Artificial neural networks require significant computational power; therefore they are often implemented on dedicated hardware architectures. Field Programmable Gate Arrays (FPGAs) provide a new approach to the implementation of ANNs. All computations on FPGAs are carried out simultaneously, therefore, they allow for better modeling of biological systems. The structure of FPGAs can be described as many blocks connected together *via* programmable interconnections. The main advantage of FPGAs is the parallelism of computing and reconfiguration properties [25,26]. From point of view of the features of biological neural networks, their hardware implementation is better and more efficient than the software one [27]. Many of scientists have made great efforts to implement artificial neural networks using programmable devices [28]. For engineering applications, neural networks change in scale, topology, transfer functions and learning algorithms. A reconfigurable approach for hardware implementation of ANNs, which can fully meet real-time requirements, has been presented in [29]. FPGAs allow for digital implementation of ANNs [30,28], in contrast to the dominant trend of software or analog implementation [27]. Jamro et al. [31] has presented a novel Parallel-Serial Architecture for Neural Networks (PSAN) which was optimized for digital hardware implementation. The proposed architecture is especially efficient for multi-layer neural networks, and it was developed and tested for an already trained feed-forward network. A reconfigurable approach for hardware implementation of ANNs has been proposed in [29], and by comparison with other implementations, it has been shown that this approach displays the highest performance.

In this study, a hardware implementation of an artificial neural network for condition monitoring of the planetary gearbox is presented. The implementation was done on a Field Programmable Gate Array, and some modifications of chosen Learning Vector Quantization neural network were proposed, in order to improve the learning process and to reduce the hardware resources. Additionally, the experiment was conducted to build a training data set and to verify the neural classifier. Developed system is characterized by high performance, high reliability and low power consumption. The developed system can be used as an independent monitoring system, or it can be combined with traditional data acquisition systems. The method was tested in laboratory conditions but in application for large-scale machinery it has to be tuned according to the kinematic and operational parameters, as well as the investigated failures of the object.

2. Artificial neural networks for classification

2.1. Artificial neural networks

To present a model of an artificial neural network it is necessary to discuss the construction and functions of a nervous system. A nervous system is built-up of basic cells which are known as neurons, they have the ability to transfer and change electrical signals. The branched projections of a neuron that conduct the electrochemical stimulation received from other neural cells to the cell body are called dendrites. One dendrite is thicker and longer than the others and is covered by a myelin sheath – this is the axon. The axon allows for connection of the neurons by synaptic terminals. The synaptic terminal allows for transmission of the electrochemical potential between the neurons by mediators [32]. The action of a neuron is based on accumulation of the electrochemical potential from the other neurons. The incoming signals to a cell body change regarding the mediators of synaptic connections. If the nucleus of a neuron reaches a sufficiently large potential in a sufficiently short period of time, then excitation of the neuron occurs and transition of the electrochemical signal to other neurons *via* the axon