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Editorial
Advances in Machine Fault Diagnosis

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1. Introduction

The growing need for intelligent machines, the outreach for more efficient use of the machines in industry, and the development of Industry 4.0 and 5.0 ideologies have pushed forward the field of machine fault diagnosis. Research in the field is receiving significant attention in academia and industry due to the importance of identifying underlying causes of machine faults. The overall objective of different machine fault diagnosis methods is to develop an effective diagnosis procedure. Recent methodological advances permit compressive machine fault diagnosis, providing detailed information, essential for the prevention of future machine failures.

Some of the most promising approaches for the continuous advancement of fault detection and diagnosis technologies are advanced digital signal processing, vibration-based condition monitoring, modal and operational mode analysis, neural network analysis, and machine learning. Moreover, there is often a combination and cross-usage of the methods. With the development of different IT solutions, the number and usability of methods is rapidly growing. Even some of the older and known methods, proposed years ago but discarded due to problems with automation or the need for additional computational resources, have found new life and promising results due to advances in measurement technologies and computational power. The opportunities opened by Internet of things (IoT) and cloud computing services are breaking new ground and shifting paradigms in the field.

Artificial intelligence (AI) has become one of the most transformative technological revolutions since, e.g., the invention of the steam or electric engines. Robustness, precision automated (online) learning, and the capacity to handle complex data are some of the AI attributes that hold significant potential for machine fault diagnosis. In hand with IoT and cloud computing, the emerging AI-based diagnostic methods are proving themselves to be powerful tools for the future.

The main objective of this Special Issue (SI) was to gather state-of-the-art research contributing recent advances in machine fault diagnosis and, hopefully, to outline future research directions in the field.

2. Review of Issue Contents

This SI compiles 11 papers from authors and research groups active in the field of machine fault diagnosis. As the topic itself is interdisciplinary, the papers presented in this SI have different viewpoints. Some look at the electrical side of machines, while others concentrate on the mechanical issues. However, most of the papers cover the integral part of measurement technology and related signal processing, essential for successful prognostic and diagnostic procedures. One of the papers is a comprehensive review paper, while the other ten focus on research aspects of machine fault diagnosis.

The only review paper of the SI [1] provides an overview of the trends and challenges in intelligent condition monitoring of electrical machines using machine learning. As the world is moving toward Industry 4.0 standards, the problems of limited computational power and available memory are decreasing day by day. A significant amount of data with

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a variety of faulty conditions of electrical machines working under different environments can be handled remotely using cloud computation. Moreover, the mathematical models of electrical machines can be utilized for the training of AI algorithms. Nevertheless, the collection of big data is a challenging task for the industry and laboratory because of limited resources. Some promising machine learning-based diagnostic techniques are presented in terms of their attributes.

The authors of [2] analyzed the frequency interaction of the turbine block in a stand with respect to the magnitude of the error in measuring the turbine's power. They proposed an algorithm for constructing a dynamic analysis during the formation of a wave field of a stand for testing turbines. The research algorithm involved the use of theoretical solutions of nonlinear wave processes using linear oscillations, refined by experiments. The diagnostic model can determine the technical condition of the stand's elements and determine the causes of the discrepancies between the calculated and measured turbine power values. To clarify the stiffness coefficients between the stand's elements, a modal analysis was used to obtain the range of their changes depending on the external dynamic load, which made it possible to assess the impact of changes in the frequency interaction conditions on the turbine power measurement for different test modes. The conditions for amplifying the amplitude of oscillations at their eigenfrequencies were obtained, and the value of the possible deviation of the expected power value at its measurement for specific modes of the turbine was calculated.

Condition monitoring of induction motors using transient modeling and recovery of a nonstationary fault signature was analyzed in [3]. The authors presented the modeling and the broken rotor bar fault diagnostics using time–frequency analysis of the motor current under an extended startup transient time. The transient current-based nonstationary signal was retrieved and investigated for its time–frequency response to segregate the rotor faults and spatial harmonics. For studying the effect of reduced voltage on various parameters and the theoretical definition of the fault patterns, a winding function analysis-based model is presented. Moreover, an algorithm to improve the spectrum legibility was proposed. It was shown that, through efficient utilization of the attenuation filter and consideration of the area containing the maximum power spectral density, the diagnostic algorithm gave promising results.

Machine learning advances and its utilization in machine fault diagnosis were outlined in [4], where the authors dealt with transfer learning-based fault diagnosis under data deficiency. In fault diagnosis studies, data deficiency, meaning that the fault data for the training are scarce, is often encountered, which may greatly deteriorate the performance of the fault diagnosis. To solve this issue, the transfer learning approach was employed to exploit the neural network trained in another (source) domain where enough fault data were available in order to improve the neural network performance of the real (target) domain. While there have been similar attempts of transfer learning in the literature to solve the imbalance issue, they were related to the sample imbalance between the source and target domain, whereas this study considered the imbalance between the normal and fault data. To illustrate this, normal and fault datasets were acquired from the linear motion guide, in which the data at high and low speeds represented the real operation (target) and maintenance inspection (source), respectively. The effect of data deficiency was studied by reducing the number of fault data in the target domain, and comparing the performance of transfer learning, thereby exploiting the knowledge of the source domain and the ordinary machine learning approach without it. By examining the accuracy of the fault diagnosis as a function of the imbalance ratio, it was found that the lower bound and interquartile range of the accuracy were improved greatly by employing the transfer learning approach.

Feature extraction for bearing fault detection using wavelet packet energy and fast kurtogram analysis was presented in [5]. In this paper, an integrated method for fault detection of bearings using wavelet packet energy and a fast kurtogram was proposed. The method consisted of three stages. Firstly, several commonly used wavelet functions were compared to select the appropriate wavelet function for the application of wavelet packet energy. Then, the analyzed signal was decomposed using wavelet packet energy, and the energy of each decomposed signal was calculated and selected for signal reconstruction. Secondly, the reconstructed signal was analyzed by fast kurtogram to select the best central frequency and bandwidth for the band-pass filter. Lastly, the filtered signal was processed using the squared envelope frequency spectrum and compared with the theoretical fault characteristic frequency for fault feature extraction. The procedure and performance of the proposed approach were illustrated and estimated using simulation analysis, proving that the proposed method can effectively extract the weak transients. Moreover, the analysis results of gearbox bearing and rolling bearing cases showed that the proposed method can provide more accurate fault features compared with the individual fast kurtogram method.

Fault diagnosis of industrial robot applications using machine learning was the main topic of [6], which dealt with exploiting generative adversarial networks as an oversampling method for fault diagnosis of an industrial robotic manipulator. Data-driven machine learning techniques play an important role in fault diagnosis, safety, and maintenance of the industrial robotic manipulator. However, these methods require data that are hard to obtain, especially data collected from fault condition states; furthermore, without enough and appropriated (balanced) data, acceptable performance should not be expected. Generative adversarial networks (GANs) are receiving significant interest, especially in the image analysis field due to their outstanding generative capabilities. This paper investigated whether or not GAN can be used as an oversampling tool to compensate for an unbalanced dataset in an industrial manipulator fault diagnosis task. A comprehensive empirical analysis was performed by taking into account six different scenarios for mitigating the unbalanced data, including classical under- and oversampling methods. In all cases, a wavelet packet transform was used for feature generation while a random forest was used for fault classification. Aspects such as loss functions, learning curves, random input distributions, data shuffling, and initial conditions were also considered. A nonparametric statistical test of hypotheses revealed that the GAN-based fault diagnosis outperformed both under- and oversampling classical methods.

Novel models for induction machine diagnosis were described in [7], where the authors presented a hybrid finite element method/analytical model of a three-phase squirrel cage induction motor solved using parallel processing for reducing the simulation time. The growing development of AI techniques can lead toward more reliable diagnostic algorithms. The biggest challenge for AI techniques is that they need a big amount of data under various conditions to train them. These data are difficult to obtain from the industries because they contain low numbers of possible faulty cases, as well as from laboratories, because a limited number of motors can be broken for testing purposes. The only feasible solution is mathematical models, which in the end can become part of advanced diagnostic techniques. The benefits of analytical and numerical models for their speed and accuracy, respectively, can be exploited by making a hybrid model. Moreover, the concept of cloud computing can be utilized to reduce the simulation time of the finite element model. In this paper, a hybrid model solved on multiple processors in a parallel fashion was presented. The results depicted that, by dividing the rotor steps among several processors working in parallel, the simulation time was considerably reduced.

Under different degradation conditions, the complexity of natural oscillation of the piston pump will change, as stated by the authors of [8]. Given the difference in the characteristic values of the vibration signal under different degradation states, this paper presented a degradation state recognition method based on improved complete ensemble empirical mode decomposition with adaptive noise (ICEEMDAN) and extreme gradient boosting (XGBoost) to improve the accuracy of state recognition. Firstly, ICEEMDAN was proposed to alleviate the mode mixing phenomenon, which was used to decompose the vibration signal and obtain the intrinsic mode functions (IMFs) with less noise and more physical meaning; subsequently, the optimal IMF was found using the correlation coefficient method. Then, the time domain, frequency domain, and entropy of the effective IMF were calculated, and the new characteristic values which can represent the degradation state were selected by principal component analysis (PCA) to realize dimension reduction. Lastly, the abovementioned characteristic indices were used as the input of the XGBoost algorithm to achieve the recognition of the degradation state. In this paper, the vibration signals of four different degradation states were generated and analyzed through the piston pump slipper degradation experiment. By comparing the proposed method with different state recognition algorithms, it was found that the method based on ICEEMDAN and XGBoost was accurate and efficient, with an average accuracy rate of more than 99%.

Planetary gearboxes were the research object in [9]. The movement of the gear is a typical complex motion and is often under variable conditions in real environments, which may render vibration signals of planetary gearboxes nonlinear and nonstationary. It is more difficult and complex to achieve fault diagnosis than to effectively fix the axis gearboxes. A fault diagnosis method for planetary gearboxes based on an improved complementary ensemble empirical mode decomposition (ICEEMD)/time–frequency information entropy and variable predictive model-based class discriminate (VPMCD) was proposed in this paper. First, the vibration signal of planetary gearboxes was decomposed into several intrinsic mode functions (IMFs) using the ICEEMD algorithm, which was used to determine the noise component as a function of the magnitude of the entropy, as well as to remove the noise components. Then, the time–frequency information entropy of the intrinsic modal function under the new decomposition was calculated and regarded as the characteristic matrix. Lastly, the fault mode was classified using the VPMCD method. The experimental results demonstrated that the proposed method can not only solve the fault diagnosis of planetary gearboxes under different operation conditions, but also be used for fault diagnosis under variable operation conditions.

The authors of [10] dealt with the condition monitoring of rotating machinery, in an effort to avoid disastrous failure and guarantee safe operation. Vibration-based fault diagnosis showed the most attractive properties for fault diagnosis of rotating machinery (FDRM). Recently, Lempel–Ziv complexity (LZC) was investigated as an effective tool for FDRM. However, LZC only performs single-scale analysis, which is not suitable for extracting the fault features embedded in a vibrational signal over multiple scales. In this paper, a novel complexity analysis algorithm, called hierarchical Lempel–Ziv complexity (HLZC), was developed to extract the fault characteristics of rotating machinery. The proposed HLZC method considers the fault information hidden in both low-frequency and high-frequency components, resulting in a more accurate fault feature extraction. The superiority of the proposed HLZC method in detecting the periodical impulses was validated by using simulated signals. Meanwhile, two experimental signals were utilized to prove the effectiveness of the proposed HLZC method in extracting fault information. Results showed that the proposed HLZC method had the best diagnosing performance compared with LZC and multiscale Lempel–Ziv complexity methods.

Last, but not least, the authors of [11] researched problems arising in the bearings and shafts of machines. Bearing preload significantly affects the running performance of a shaft-bearing system including the fatigue life, wear, and stiffness. Due to the mounting error, the bearing rings are often angularly misaligned. The effects of the combined bearing preload and angular misalignment on the fatigue life of ball bearings and a shaft-bearing system were analyzed in this paper. The contact force distribution of the angular contact ball bearings in the shaft-bearing system was investigated using the system model. The system model included the bearing model, whereas the shaft model was verified by comparing it with the manufacturer's manual and the results from other theoretical models, revealing a difference within 3% between the results from the present bearing model and the manufacturer manual. The global optimization method was used to solve the ball element displacements and friction coefficients, which improved the computation efficiency of the model. The fatigue life results showed that the system life at the optimal angular misalignment was more than 1.5 times that without angular misalignment at the low preload value, and this ratio decreased as the preload value increased.

3. Conclusions

This SI presents new and innovative research addressing some of the many scientific and technological challenges associated with the quickly evolving field of machine fault diagnosis. It must be emphasized that, with the growing efficiency needs and higher degrees of automation, in hand with novel opportunities emerging as a result of IT solutions and AI possibilities, the necessity of machine fault diagnosis is growing and the advances in the field are accelerating. The advanced techniques used for diagnostic and prognostic processes rely on a deeper understanding of automated and numeric methods and models, in order to ensure a safer and more innovative future for all fields of industry. The studies contained within this volume provide a valuable basis for the research and engineering community dealing with machine diagnosis, highlighting open trends for future development.

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