Applications of Artificial Neural Networks (ANNs) to Rotating Equipment

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Abstract

Rotating equipment is the beating heart of nearly all industrial plants and specifically plays a vital role in oil and power industries. In spite of all research which has been carried out so far to discover accurate dynamics of this kind of equipment, there are still many unknown and unexpected problems on operational sites which need to be solved in order to approach to the optimal operational point of rotary machines. Fortunately, Artificial Neural Networks (ANNs) can provide appropriate solutions to many of these problems. In this paper, a general overview of different applications of ANNs to Industrial rotating equipment is presented. These applications cover a variety of areas including condition monitoring, sensor validation, fault diagnosis, system identification and control. The advantages of using ANNs for each application are discussed briefly by providing practical examples.

Keywords: neural network, rotating equipment, rotating machine, oil and power industry

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Introduction

According to definition, rotating equipment is a general class of mechanical equipment which moves liquids, solids or gases. Rotating machines may be divided into four main groups including drivers (turbines, motors, engines), driven equipment (compressors, pumps, mixers, fans, extruders), transmission devices (gears, clutches, couplings) and auxiliary components (lube and seal systems, cooling systems, buffer gas systems) [1].

Today, a variety of rotating equipment is being used widely in different industrial plants including (but not limited to) oil and gas industries, petrochemical plants, power plants, transmission lines, cooling systems and production lines. Rotating equipment is a very important part of any plant, not just for the huge money which is spent on manufacturing, operation and maintenance of these machines, but especially because of the vital role that they play in different plants all over the world. Rotating equipment is the beating heart of industrial plants. In many cases, if rotating equipment does not work properly in a plant, it may lead to a major problem or even to shutdown of the whole plant, which would be a real disaster especially in oil and power industries. That is why many efforts and a variety of research activities have been carried out so far in order to use rotating equipment as efficiently and reliably as possible. One of the novel approaches which has been very helpful both for manufacturers and users in solving different available problems in the field of rotating machines, is Artificial Neural Network (ANN). These problems may be found in a variety of areas such as condition monitoring, fault diagnosis, trouble shooting, maintenance, sensor validation, and control.

Artificial Neural Network (ANN)

Artificial Neural Network (ANN) is a fast-growing method which has been used in different industries during recent years. The main idea for creating ANN which is a subset of artificial intelligence is to provide a simple model of human brain in order to solve complex scientific and industrial problems. Aerospace, automotive, banking, defense, electronics, finance, insurance, manufacturing, medicine, oil and gas, robotics, speech, securities, telecommunications, and transportation are just a few areas where ANNs provide outstanding solutions. Faster computers and faster algorithms have made it possible to use neural networks to solve complex industrial problems that formerly required too much computation [2].

ANNs are high-value and low-cost tools in modelling, simulation, control, condition monitoring, sensor validation and fault diagnosis of different systems including different kinds of rotating equipment. They learn from the data obtained from a system instead of learning from a specific program. ANNs can solve a variety of problems in optimization, pattern recognition, clustering, function approximation, time series analysis, prediction and validation.

A neural network model is a group of interconnected artificial units (neurons) with linear or nonlinear transfer functions. Neurons are arranged in different layers including input layer, hidden layer(s) and output layer. The number of neurons and layers depends on the complexity of the system which is to be modeled. ANNs learn the relation between inputs and outputs of the system through an iterative process called training. Each input into the neuron has its own associated weight. Weights are adjustable numbers which are determined during training the network. Figure 1 shows a simple structure of a typical ANN with four inputs, one output and four neurons.

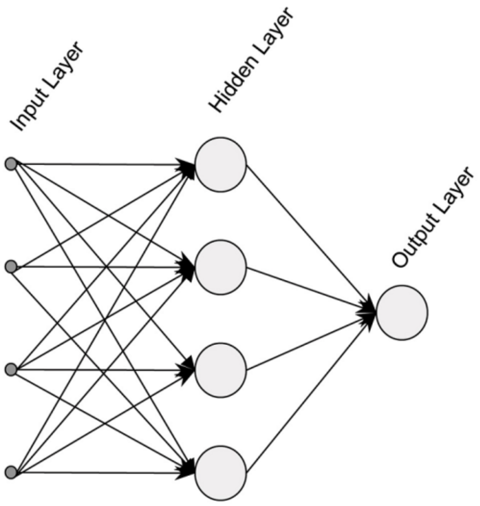

Figure 1: A simple structure of a typical Artificial Neural Network (ANN) with input, hidden and output layers

Models for rotating equipment can be constructed in different ways based on the flexibility that ANNs provide. This flexibility is based on the number of neurons, number of hidden layers, values of the weights and biases, type of the activation function, structure of the network, training styles and algorithms as well as data structure. However, the best structure is the one which can predict behavior of the system as accurately as possible.

It is really difficult to build an accurate mathematical model of many rotating machines such as gas turbines, turbo pumps and turbo compressors through physical laws because of complexity and interconnections of the system which lead to coupled nonlinear mathematical equations. That is why ANN, as a Data-driven model has been considered as a suitable alternative to physical model during the last few decades. ANN-based models can be created directly from the operational data from an actual rotating equipment or simulated data from original equipment manufacturers (OEMs) performance. Simulated data may be used when operational data are not available. The obtained data should cover the whole operational range of the system. All transient data during start or stop process should be removed from the collected data before the modeling process.

When training a neural network using special software such as Neural Network Toolbox in MATLAB, the obtained data from rotating equipment are divided into three subsets as training, validation and test data. The training set is used for computing the gradient and updating the network weights and biases. The validation data are used to stop training early if further training on the primary data will hurt generalization to the validation data. Test data set can be used to measure how well the network generalizes beyond training and validation data [3].

Selecting the right parameters of rotating equipment as inputs and outputs of the neural network is very important for making an accurate and reliable model. The availability of data for the selected parameters, system knowledge for identification of interconnections between different parameters and the aim for making a model are basic factors in choosing appropriate inputs and outputs. Accuracy of the selected output parameters can be examined by sensitivity analysis.

ANNs have many advantages in modelling, simulation and control of different kinds of rotating equipment compared with analytical methods. They are quite suitable to learn various types of information. Limited knowledge of physics of a system is not a major problem in the case of using ANNs. They are used for modelling and simulation of nonlinear systems that are difficult to be modeled and simulated with traditional methods and techniques. The capability to be used for classification and function approximation in nonlinear systems is another advantage of this kind of artificial intelligence. ANNs have high flexibility and robustness in modeling, simulating and diagnosing the behavior of rotating machines even in the presence of inaccurate input data. They can provide high computational speed for complicated tasks that require rapid response such as real-time processing of several simultaneous signals. ANNs can also be used to improve efficiency and productivity of energy in rotating equipment.

Some researchers criticize ANNs for their disadvantages. For instance, the prediction error of AANs may be quite high when the area in which they were trained, does not cover their operational field. Besides, most common neural networks need to be trained by real data sets instead of simulated ones. The problem is that the real data sets are sometimes unavailable or very difficult to obtain. However, despite some disadvantages, ANNs are still considered as powerful tools in solving many problems in different professional fields such as engineering.

Applications of ANN

Condition Monitoring

Condition monitoring is considered as a major part of predictive maintenance. It assesses the operational health of rotating equipment, in order to provide early warning of potential failure such that preventative maintenance action may be taken [4].

Condition monitoring is a very helpful tool in maintenance planning and can be used to avoid unexpected failures. Lost production, overtime, and expediting costs can be effectively prevented by predicting failures before any serious damage occurs in the system. To minimize the maintenance costs for very expensive and important machines such as rotating equipment, it is necessary to monitor the operating conditions of vital and sensitive parts of the equipment and to obtain their related data continuously for further analysis.

Good condition monitoring in rotating equipment reduces the number of wrong decisions, minimizes the demand for spare parts and reduces maintenance costs. A good maintenance system should be capable of monitoring parameters such as vibration, temperature, pressure, rotational speed and oil quality. Besides, it should be able to predict the future state of the system and to prevent unwanted shutdowns as well as fatal breakdowns.

Since all the requirements for building the monitoring model are data driven from the rotating machine, ANN offers a cost-effective and reliable approach to condition monitoring. Using artificial neural networks, collected data regarding the condition of the machinery can be classified and trained in order to generalize a method for data analysis at any time of the measurement.

As a practical example of condition monitoring of rotating equipment, one can refer to the research titled "Intelligent condition monitoring of a gearbox using artificial neural network" (Rafiee et al., 2006). In this research, a new procedure was created to experimentally recognize gears and bearings faults of a typical gearbox system using a multi-layer perceptron neural network [5].

Fault Diagnosis

Fault diagnosis plays an important role in the efforts for gas turbine owners to shift from preventive maintenance to predictive maintenance, and consequently to reduce the maintenance cost [6]. It concerns with monitoring a system in order to identify when a fault has occurred as well as to determine the type and location of the fault.

Whereas ANNs are adaptable to continuously variable data, they are replacing the traditional methods and systems for fault diagnosis. During recent years, new methodologies using ANNs have been utilized in order to evaluate vibrations and recognize fault presence. These methodologies allow operators to diagnose faults, which were not considered in the training of the neural network. For instance, the trained neural network may detect availability of a failed bearing or imbalanced shaft, even if these types of data were not available in the training data set.

Different criteria should be considered in selecting appropriate neural network architecture for fault diagnostics of rotating equipment. The network should be capable of adapting itself quickly to potential changes such as new information or system modifications in order to maintain and improve system performance. It should also be capable of being trained rapidly and stably by new training data. Besides, the network should have the capability of replacing alternatives, if the first diagnosis is incorrect. That is because the internal state of the equipment is not known enough and signal data cannot always show the accurate conditions of the system.

As an example of application of ANN to fault diagnosis of rotating machines, an ANN was used for fault diagnosis of a medium-size industrial gas turbine (Arriagada et al., 2003). The researchers obtained the real required data set which included only parameters that were actually measured in the real engines, from one healthy and ten faulty engine conditions. The trained network was able to make a diagnosis about the gas turbine's condition when new data was presented to it. The results of the research showed that an ANN-based fault diagnosis system was capable of fault isolation and identification with high reliability. Besides, the system was also able to identifying many fault types at an early stage, before they were fully developed and became obvious. Figure 2 shows a schematic drawing of the ANN and the interpretation of the outputs in a graphical display [7].

As it can be seen from the ANN architecture, the inputs correspond to the 14 measured parameters in the real engines, as well as the ones controlled by the operators and the control system. They include ambient temperature, inlet guide vanes angle, mass flow rate, fuel flow rate, load, pressure and temperature in different sections of the turbine, etc. The desired outputs from the ANN are unique combinations of 28 binary numbers arranged in a graphical display as shown in Figure 2. The training process of the ANN stopped when it showed the best performance based on a selected number of hidden neurons and weights for the network. The ANN can be named 14-H-28 according to its structure [7].

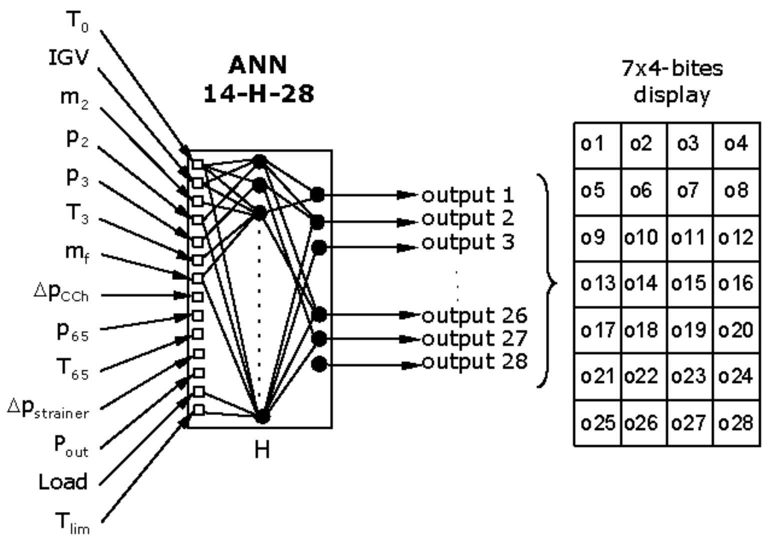

Figure 2: Schematic drawing of the ANN and the interpretation of the outputs in a graphical display [7]

Sensor Validation

Sensors are essential parts of any rotating equipment. Without reliable and accurate sensors, monitoring and control system of the equipment cannot work properly. If any of the sensors fails to send signal, rotating equipment may not operate optimally and may even face shutdown.

Sensor validation is detecting, isolating and reconstructing a faulty sensor. Some sensors may fail to report correct data due to different reasons or may even become unavailable because of failure or maintenance activities. Sensor validation can improve reliability and availability of the system, and reduce maintenance costs. It enhances reliability and safety for the equipment and personnel respectively. Sensor validation is also an effective tool to prevent unwarranted maintenance or shutdown. It has a considerable effect in increasing equipment's lifetime and assuring reliable performance of the equipment. It can strengthen automation of the system by providing valid data for diagnostic and monitoring systems.

In 2011, Palmé et al. presented a method for evaluating sensor accuracy in order to minimize the need for calibration and to avoid shutdowns due to sensor faults [8]. The proposed method was based on training ANNs as classifiers to recognize sensor drifts. The method was evaluated on one single-shaft and one twin-shaft gas turbine. According to the results, the proposed method is capable of early detection of sensor drifts for both types of machines. The results also show that use of ANNs for sensor validation leads to more cost-effective maintenance and can increase availability as well as reliability of power plants [8].

System Identification and Modelling

System identification infers a mathematical description, a model of a dynamic system from a series of measurements of the system [9]. Although much research has been done so far in the field of modelling of rotating equipment using mathematical and experimental methods, there are still unpredictable events during operation of rotating machines because of the complexity and nonlinear behavior of these systems. Therefore, there is a strong motivation for many researchers to continue to work in this field. They want to apply new methodologies in order to make a reliable prototype model for rotating machines. Such a model can predict the behavior of the system as accurately as possible. Fortunately, ANNs can be used to model a wide class of systems such as rotating equipment in many applications. They are powerful tools in system identification and modelling, because of their excellent ability to approximate uncertain nonlinearity to a high degree of accuracy. The main steps for identification and modelling of a dynamic system are data collection, model structure selection, model estimation using appropriate software, and model validation.

As a practical example of using ANNs to model performance characteristics in rotating equipment, one can refer to an application to deep well pumps with splitter blade [10]. Figure 3 shows the ANN model with 3 inputs, 20 hidden neurons and 2 outputs. [10]

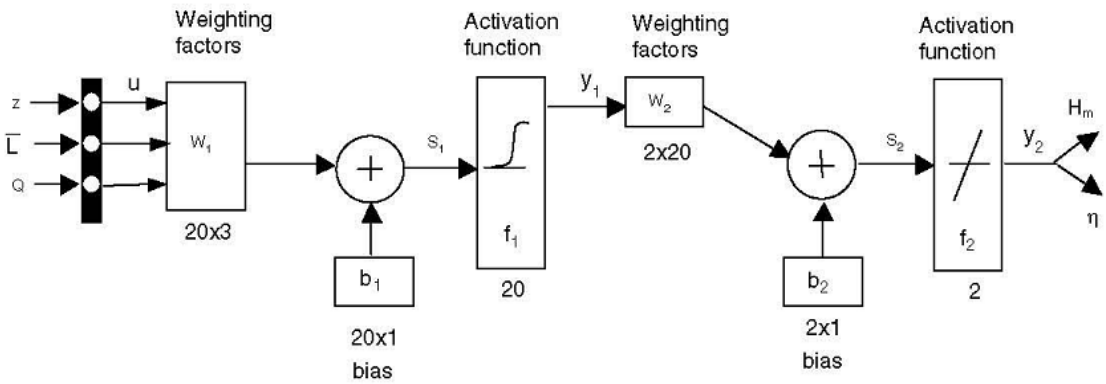

Figure 3: ANN model of a Deep Well Pump with 3 inputs, 20 hidden neurons and 2 outputs [10]

The performance characteristics of the pumps include head-flow rate, efficiency-flow rate, and power-flow rate based on different values for blade number (z), non-dimensional splitter blade length (L) and flow rate (Q) as the inputs of the ANN model. Head (H_m), and efficiency (η) were considered as the output parameters of the system. In Figure 3, u is the input vector; W_1 and W_2 are matrices containing weighting factors for the input layer and hidden layer, respectively. The output vectors for the hidden layer and output layer are y_1 and y_2 respectively, which contains the head and efficiency. Bias vectors for the input layer and hidden layer are b_1 and b_2 respectively [10].

Control

Fundamental to any control system is the ability to measure the output of the system, and to take corrective action if its value deviates from some desired value. This in turn necessitates a sensing device [11].

Control as a branch of engineering deals with the behavior of dynamical systems. The output performance of the equipment which is under control is measured by sensors. These measurements can be used to give feedback to the input actuators to make corrections toward desired performance. In spite of the active research in this field, there are still increasing demands for accurate dynamic models and controllers, in order to investigate the system response to disturbances and improve existing control systems. ANN's have been considered as an acceptable solution to many outstanding problems in modelling and control of nonlinear systems such as gas turbines, pumps and compressors. In control design process, a neural network may directly implement the controller (direct design). In this case, a neural network will be trained as a controller based on some specified criteria. It is also possible to design a conventional controller for an available ANN model (indirect design). In this approach, the controller is not itself a neural network.

There are many different approaches to using neural networks in control systems such as model reference control, NARMA control and model predictive control. For model reference control, the controller which is a neural network is trained to control a plant so that it follows a reference model. The neural network plant model is used to assist in training of the controller. For NARMA control, the controller is just a rearrangement of the plant model and for model predictive control; the plant model is used to predict future behavior of the plant. Besides, an optimization algorithm is used to select the control input that optimizes performance [3].

As an example of application of ANNs in control of rotating machine, one can refer to the research of Jurado et al. about designing a neuro-fuzzy controller for a gas turbine in biomass-based electric power plant [12]. The controller regulates both the gas turbine and the gas turbine generator. Two fuzzy logic controllers were developed using speed and mechanical power deviations, and a neural network was designed to tune the gains of the fuzzy logic controllers based on the operating conditions of the biomass-based electric power plant. It was shown that by tuning the fuzzy logic controllers, optimal time domain performance of the system can be achieved in a wide range of operating conditions compared to fixed parameter fuzzy logic controllers and PID controllers [12].

Conclusion

Artificial Neural Networks (ANNs) have been shown to be robust and reliable tools in many industrial applications. They have been utilized to solve many operational problems especially in the area of rotating equipment in oil and power industries. They provide outstanding solutions to the problems of complex systems with nonlinear dynamics. In this paper, a brief overview of important applications of ANNs to rotating equipment was presented. Applications of ANNs for condition monitoring, sensor validation, fault diagnosis, system identification and control were discussed briefly. For each application, a practical example of related research activities was provided. ANNs will play an increasingly important role in the area of rotating machines in the near future.

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