AGH

AKADEMIA GÓRNICZO-HUTNICZA IM. STANISŁAWA STASZICA W KRAKOWIE

FIELD OF SCIENCE: ENGINEERING AND TECHNOLOGY

SCIENTIFIC DISCIPLINE: AUTOMATION, ELECTRONIC AND ELECTRICAL ENGINEERING

SUMMARY OF DOCTORAL THESIS

Automated fault detection of large turbomachinery using Machine Learning on transient data

Author: mgr inż. Mateusz Tadeusz Zabaryłło

First supervisor: Prof. dr hab. inż. Tomasz Barszcz
Assisting supervisor: Dr hab. inż. Mariusz Banaszkiewicz

Completed in: AGH University of Science and Technology in Krakow, Faculty of Electrical Engineering, Automatics, Computer Science and Biomedical Engineering

Krakow, 2022

AKADEMIA GÓRNICZO-HUTNICZA IM. STANISŁAWA STASZICA W KRAKOWIE

DZIEDZINA NAUKI INŻYNIERYJNO-TECHNICZNE

DYSCYPLINA AUTOMATYKA, ELEKTRONIKA I ELEKTROTECHNIKA

AUTOREFERAT ROZPRAWY DOKTORSKIEJ

Metoda zautomatyzowanego wykrywania uszkodzeń dużych maszyn wirnikowych z wykorzystaniem danych ze stanów przejściowych

Autor: mgr inż. Mateusz Tadeusz Zabaryłło

Promotor rozprawy: Prof. dr hab. inż. Tomasz Barszcz
Promotor pomocniczy: Dr hab. inż. Mariusz Banaszkiewicz

Praca wykonana: Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie, Wydział Elektrotechniki, Automatyki, Informatyki i Inżynierii Biomedycznej

Kraków, 2022

Content

Abstract

Detection and identification of malfunctions in large rotating machines are among the most critical subjects in the diagnostics of utility power generation machinery. The factor that creates significant obstacles in analyzing such large research objects is the complexity of the vibration response for the entire shaft line train, composed of several parts. There are several procedures and methods to detect and identify anomalies during the steady-state operation of turbomachinery. More important in fault diagnosis is the analysis of transient states of these machines. Key disadvantage of these methods is involvement of human experts with strong experience.

The aim of the research was to propose a complete system of automatic fault diagnosis of large rotating machines based on their responses in transient states - particularly during changes in rotational speed.

The research problem, i.e., the detection and identification of failures during the commissioning or shutdown of a high-power turbine set, was solved by analyzing a number of diagnostic tests performed by the author on facilities installed in utility power plants and simulating specific malfunctions at a test rig. The databases with diagnostic tests contained both the responses of fault-free turbine sets and those with specific damages confirmed during diagnostic tests on objects. The author used data from a portable diagnostic device. The author developed and proposed two methods: the Operating Envelope - OpEn method (for automatic fault detection during transient states) and the Multidimensional Data Driven Decomposition - MD3 method (for automatic fault identification). Determining the reference data and preparing the data from the current transient state is based on the Cubic Spline interpolation (to standardize the intervals for which all data will be analyzed). In the failure detection method (OpEn), the author used a concept similar to the signal envelope (Spectrum Envelope) to determine the region of acceptance of the correctness of the turbine set response. In his analysis, the Differential Evolution (DE) algorithm was used to automatically identify the parameters of the decomposed functions derived from the Genetic Algorithms (GA) family of genetic algorithms. The remaining tools that make up the entire proposed system are, for the detection method: two- and three-dimensional acceptance regions for each of the sensors of individual parts of the turbine set, and for the identification method: a set of three scenarios with appropriately modified decomposition functions along with a measure of their matching. All the methods were tested on data from a simulated environment on a laboratory stand and data from real turbo generators.

Streszczenie

Wykrywanie i identyfikacja uszkodzeń dużych maszyn wirnikowych jest jednym z najważniejszych zagadnień diagnostyki maszyn energetycznych dużej mocy. Czynnikiem stwarzającym duże przeszkody w analizie tak dużych obiektów badawczych jest złożoność ich odpowiedzi drganiowej dla linii wałów, składającej się z kilku części. Istnieje szereg procedur i metod pozwalających wykrywać i identyfikować anomalie podczas pracy w stanach ustalonych maszyn energetycznych. Ważniejsza pod względem diagnostyki uszkodzeń jest jednak analiza stanów przejściowych tych maszyn. Zasadniczą wadą obecnego podejścia jest konieczność angażowania ekspertów z dużym doświadczeniem, co jest bardzo kosztowne i pracochłonne.

Celem pracy było zaproponowanie kompletnego systemu automatycznej diagnostyki uszkodzeń dużych maszyn wirnikowych na bazie ich odpowiedzi w stanach przejściowych – w szczególności podczas zmiany prędkości obrotowej.

Problem badawczy, to jest detekcja i identyfikacja uszkodzeń podczas uruchomienia lub odstawienia turbozespołu dużej mocy został rozwiązany poprzez analizę szeregu badań diagnostycznych wykonanych przez autora na obiektach zainstalowanych w elektrowniach zawodowych oraz symulację konkretnych niesprawności na stanowisku laboratoryjnym. Bazy danych z badaniami diagnostycznymi zawierały zarówno odpowiedzi turbozespołów wolnych od uszkodzeń, jak i z konkretnymi uszkodzeniami zweryfikowanymi w trakcie badań diagnostycznych na obiektach. Autor w poniższej pracy używał danych pochodzących z przenośnego urządzenia diagnostycznego. Autor opracował i zaproponował dwie metody: Operating Envelope – OpEn (do automatycznej detekcji uszkodzeń podczas stanów przejściowych) oraz Multidimensional Data Driven Decomposition – MD3 (do automatycznej identyfikacji niesprawności). Ustalenie danych referencyjnych jak i przygotowanie danych z aktualnego stanu przejściowego jest oparte na interpolacji Cubic Spline (w celu ujednolicenia interwałów, dla których będzie przeprowadzana analiza wszystkich danych). W metodzie detekcji uszkodzeń (OpEn) autor wykorzystał koncepcję zbliżoną do obwiedni sygnału (Spectrum Envelope) w celu określenia regionu akceptacji poprawności odpowiedzi turbozespołu. Do automatycznej identyfikacji parametrów dekomponowanych funkcji, został wykorzystany algorytm Differential Evolution (DE), który wywodzi się z rodziny algorytmów genetycznych Genetic Algorithms (GA). Pozostałymi narzędziami składającymi się na cały zaproponowany system są: dla metody detekcji: dwu- i trójwymiarowy rejon akceptacji dla każdego z czujników poszczególnych części turbozespołu, a dla metody identyfikacji: zbiór trzech scenariuszy z odpowiednio zmodyfikowanymi funkcjami dekompozycji wraz z miarą ich dopasowania. Wszystkie metody zostały przebadane na danych pochodzących z symulowanego środowiska na stanowisku laboratoryjnym oraz na danych z obiektów rzeczywistych.

1. Motivation and Aim of Dissertation

Fault detection and identification is not an easy task for condition monitoring of the large rotating machinery. The reliable vibration measurements of high-power energy machines requires an advanced signal processing system, including spectral analysis and order analysis. Due to fluid-film bearings used as the supporting structures of the machine, the complexity of the rotor-to-stationary part relations is even more complex. The FEM (Finite Element Method) based models are often used to analyse a rotor's behaviour but the creation, modelling and behaviour analysis of such system is extremely complex and needs a high level of technical knowledge and experience.

A maintenance strategy that enables detecting malfunctions at the early stages of their evolution should play a crucial role in facilities using these types of machinery. The best data source for assessing the technical condition is the transient data measured during start-ups and coast downs. Most of the automated methods proposed in the literature are applicable to small machines with a rolling element bearing, during a steady-state operation with a shaft considered a rigid body. Large power turbomachinery express a very different behaviour. They operate above their first critical rotational speed interval, and thus their shafts are considered flexible. To make the case more complex, these turbines are equipped with hydrodynamic sliding bearings. Such an arrangement introduces significant complexity to the analysis of the machine behaviour, and consequently, analysing such data requires advanced rotordynamics knowledge and field experience. Typically, after each transient machine data should be investigated to check whether the dynamic state is satisfactory and the machine can be operated safely. Such a step requires advanced measurement equipment, which is not always accessible, and availability of a skilled expert, which is costly and must be scheduled according to the availability.

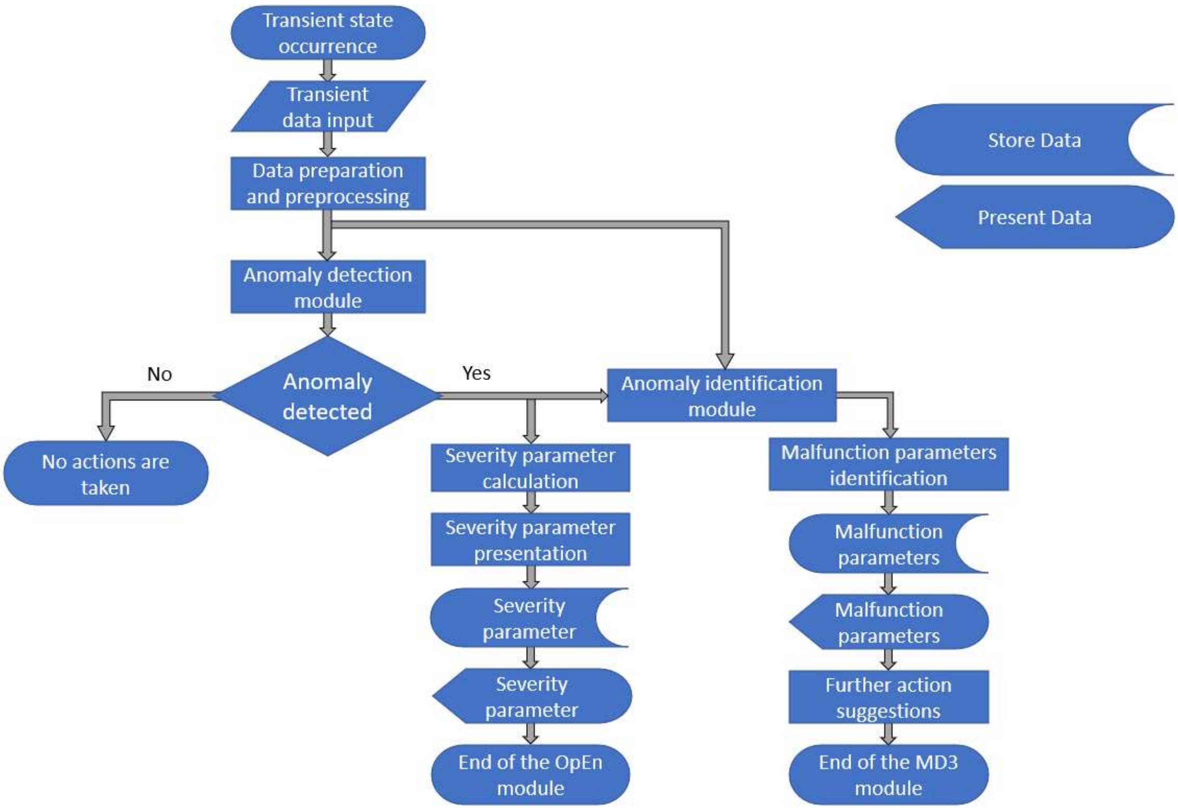
The aim of the dissertation was the research of a method to diagnose large rotating equipment in an autonomous way, so that the load on experts can be reduced to really important cases. In the dissertation the author proposes the anomaly detection method which he named the Operating Envelope (abbreviated as OpEn) and the fault identification method, which he named the Multidimensional Data Drive Decomposition (abbreviated as MDDD or MD3). Combination of both methods can be a basis of a functional and autonomous multi-channel fault detection and identification system.

2. Hypotheses

The main scientific goal of the dissertation is proving of the statement:

It is possible to detect and identify faults of the large turbomachinery by an automated algorithm using analysis of transient data.

The FDI for aforementioned system can be structured as follows:



To achieve the main hypotheses, several hypothesis were formulated across the dissertation:

I. Transient data can be used to determine different dynamic state of the machine.
II. The Cubic Spline interpolation can successfully convert the measured data to the RPM-equidistant data in order to compare them in RPM domain.
III. Anomaly of large turbomachinery during transients can be detected using the upper and lower values for individual rotational speed values (i.e., the acceptance region in the Operating Envelope method).
IV. Appropriate function combinations with different sets of function parameters can fit measured / transient state data.
    a. Resonance can be approximated by the gaussian probability function:

$$f_1 = a_1 e^{\frac{(x-b_1)^2}{c_1}}$$

b. Excessive imbalance can be approximated by the parabola function:

$$f_2 = a_2 \left(\frac{x - x_0}{x_k - x_0}\right)^2$$

c. Electrical or mechanical imperfections can be approximated by the constant function:

$$f_3 = b_3$$

where:

f_1 – Gauss function with $a_1,\ b_1, c_1$ parameters respectively,

f_2 – parabola with a_2 parameter and b_2 as a bias term respectively,

a_1 – amplitude of the Gauss function,

b_1 –placement of the resonance peak along the rotational speed axis,

c_1 – width of the resonance,

a_2 – factor related to synchronous response,

x_0 – starting point of centrifugal force response,

x_k – rotational speed range (in given transient),

b_3 – bias constant (electrical/mechanical runout).

V. Differential Evolution algorithm can optimize the decomposed function parameters that fit the transient function the best way.

VI. Fault identification of large turbomachinery malfunctions during transient state can be achieved by identifying a set of parameters for several known decomposed functions. The transient response function can be accurately represented as a sum of the simple functions:

$$\varphi_{approx} = \varphi_1 + \varphi_2 + \cdots + \varphi_n = \sum_{i=1}^{n} \varphi_i$$

where:

φ_i – decomposed function

3. Summary

In this dissertation the whole FDI system for large turbomachinery has been developed, tested and validated. The data-driven methods (OpEn and MD3) developed in this dissertation for the analysis and automatic diagnostics of failures are driven by the type and nature of data obtained during large turbomachinery measurements. Therefore, the methods proposed by the author in the doctoral dissertation are a compromise of the amount of available data and the accuracy/repeatability of the results. The dissertation is also a result of over 13 years of industrial practice combined with experience and expert knowledge in the field of signal processing, rotor dynamics and large turbomachinery.

The proposed Operational Envelope (OpEn) method can help the maintenance staff in machine operation and overhaul planning. OpEn is a novelty detection method that can be applied to the data taken during the transient state of a machine. Together with the OpEn algorithm, the author proposed a set of parameters that can be used to diagnose the transient automatically. Furthermore, those parameters can be used with other process data for better and more in-depth diagnostic purposes.

Two parameters called RMSE and "Max Out of OpEn" were shown as helpful in the automated detection of malfunctions. The other two may also be useful in the detection of other malfunctions. The OpEn 2D and OpEn 3D are an automated fault detection method for transient states. The 2D case analyses only a single feature from a single sensor. The 3D case conjuncts two vibration signal features, i.e., synchronous amplitude and its phase. Novelty detection method proposed in the dissertation can be used to detect faults over different speed spans, different amplitudes during transient states, and different sets of sensors. All these factors make this method very flexible and a powerful tool in predictive maintenance schemes for many power facilities.

The Multidimensional Data Driven Decomposition (MD3) method proposed in this thesis is designed to identify machinery faults automatically. The author's novel approach to decompose the transient into several predefined signals, enables the analysis of individual dynamics system parameters becomes easier to evaluate and assess even to unqualified personnel. The decomposed transient components are responsible for particular failure modes and, as a consequence, not only can different malfunctions be detected, but they can also be identified. These parameters can be used to track and trend the evolution of the system dynamic response parameters without the engagement of the diagnostic teams. The MD3 method can assess data during each transient in contrast to portable equipment measurement that can miss the unplanned and sudden shut-downs and start-ups. The cornerstone of the method is to decompose a transient into a set of base functions. Such functions have a simple form (Gaussian, parabolic or constant bias). Each such function has a mechanical meaning and can be used to diagnose and analyse transient responses collected during coast-downs and start-ups. The innovative MD3 method proposed in the article can increase the safety of the device and reduce the costs of electricity generation.

The author developed complete set of methods, using data-driven methodology, to automatically analyse the transient signals from large turbo sets. This allows to create the complete automated fault detection and identification system of large turbomachinery using Machine Learning approach. Such an achievement was the goal of this thesis, i.e. one can state that the goal of the dissertation was achieved.

The results of this dissertation can be used in FDI systems in commercial and industrial power plants as an autonomous diagnostic system. It can also be an extension and support for the existing diagnostic system, adding an element of automation to the diagnostic processes of the most critical machines in the enterprise.

The most important publications

- M. Zabaryłło, T. Barszcz, "Proposal of multidimensional data driven decomposition method for fault identification of large turbomachinery", Energies, ISSN 1996-1073. — 2022 vol. 15 iss. 10 art. no. 3651.
- T. Barszcz, M. Zabaryłło, "Fault detection method based on an automated operating envelope during transient states for the large turbomachinery", Journal of Vibroengineering ; ISSN 1392-8716. — 2022 vol. 24 iss. 1, S. 75–90.
- T. Barszcz, M. Zabaryłło," Automatic identification of malfunctions of large turbomachinery during transient states with genetic algorithm optimization", Metrology and Measurement Systems : quarterly of Polish Academy of Sciences, 2022 vol. 29 no. 1, s. 175–190.
- T. Barszcz, M. Zabaryłło, "Novel machine learning method for automatic detection of malfunctions of large turbomachinery during transient states", 6 August 2020 : virtual conference [Oak Brook : MFPT – a division of The Vibration Institute], [2020]. — Slajdy 1–17.
- M. Zabaryłło, A. Jabłoński, T. Barszcz, „Vector-based 3d method for fault detection of large turbomachinery", VibDiag : Vibroacoustics and diagnostics machinery, devices and structures: Poznań, 24 November 2021 : proceedings of 2nd scientific conference, — ISBN: 978-83-89333-78-0. — Str. 60.

- M. Zabaryłło, T. Barszcz, “Practical considerations of the static – couple method for large power turbomachinery”, Diagnostyka maszyn : XLV ogólnopolskie sympozjum: Wisła, — ISBN: 978-83-930581-8-1. — S. 98.
- M. Zabaryłło, T. Barszcz, “Multi-channel operational envelope method for automated fault detection”, Diagnostyka maszyn : XLVIII ogólnopolskie sympozjum : Wisła , 2022, ISBN: 978-83-964252-0-1. – S. 75.
- T. Barszcz, M. Zabaryłło, “Fault detection method based on an automated operating envelope during transient states for the large turbomachinery”, Young scientists in power engineering [Dokument elektroniczny] : II edition of the XII conference : KME, e-ISBN: 978-83-7493-156-4. — S. 176–177.
- T. Barszcz, P. Czop, M. Zabaryłło, “Development and tuning of a simplified 1D model for generation of transient states in large turbomachinery”, Proceedings of the 13th international conference on Damage Assessment of Structures : DAMAS 2019, 9–10 July, 2019, Porto, Portugal / ed. Magd Abdel Wahab. — Singapore : Springer Nature Singapore, cop. 2020. — (Lecture Notes in Mechanical Engineering ; ISSN 2195-4356). — ISBN: 978-981-13-8330-4 ; e-ISBN: 978-981-13-8331-1. — S. 541–554.
- T. Barszcz, M. Zabaryłło, “Concept of automated malfunction detection of large turbomachinery using machine learning on transient data — Metoda automatycznej detekcji niesprawności dużych turbozespołów z zastosowaniem metod uczenia maszynowego na danych ze stanów przejściowych”, ISSN 1641-6414. — 2019 vol. 20 no. 1, s. 63–71.