ERCIM "ALAIN BENSOUSSAN" FELLOWSHIP PROGRAMME

Scientific Report

First name / Family name	Hamid Asgari
Nationality	Iranian
Name of the *Host Organisation*	VTT
First Name / family name of the *Scientific Coordinator*	Emmanuel Ory
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I – SCIENTIFIC ACTIVITY DURING YOUR FELLOWSHIP

Modelling of industrial systems is a very powerful tool in solving a variety of technical problems in engineering fields, covered from basic design to manufacturing, operation, and maintenance. White-box (physics based) and black-box (data-driven based) models are two main approaches for modelling and simulation of industrial equipment and processes. When access to physics of the system and dynamic equations is impossible or limited, black-box modelling, which relies on the system data, is a very good alternative. During my fellowship at Technical Research Center of Finland (VTT), I developed white-box and black-box models of gas turbines (GT) using conventional methods (Simulink/MATLAB) and machine learning based techniques.

Gas turbines are internal combustion engines widely used in industry as main source of power for aircrafts, turbo-generators, turbo-pumps and turbo-compressors. Modelling these engines can help to improve their design and manufacturing processes, as well as to facilitate operability and maintenance of these machineries. These eventually lead to manufacturing of gas turbines with lower costs and higher efficiency at the same time. The models may also be employed to unfold nonlinear dynamics of these systems.

In my studies, a model of a single shaft gas turbine (GT) was developed by using artificial intelligence (AI). A recurrent neural network (RNN) was employed to train the datasets of the GT variables in Python programming environment by using Pyrenn Toolbox. Among different ANN algorithms for static and dynamic modellings, RNN can be employed for the modelling of dynamic industrial systems. In a recurrent neural network, each layer has a recurrent connection associated with a tap delay. This enables RNN to propagate data forward and backward, from later processing stages to earlier ones, allowing the network to have an infinite dynamic response to the input data. As a universal approximator, RNN has shown excellent dynamic ability to deal with various input and output types for modelling and simulation of industrial systems.

To approach an RNN model with a high accuracy for the gas turbine of this study, a variety of structures was considered. These structures were set up based on the data type, training algorithms, types of activation functions, number of hidden layers, number of neurons, and values of the weights and biases. The goal was to attain a structure with the high capability of accurate prediction of the GT dynamic behaviour. The most effective GT variables were employed as inputs and outputs for building a reliable model. Data availability, system knowledge, and modelling objectives were also considered as fundamental factors for the selection of the RNN inputs and outputs. A dynamic model of a low-power gas turbine, simulated in Simulink/MATLAB environment was employed for data generation. Totally, 3000 datasets were generated for 13 different GT variables.

The resulting model was validated against the test datasets. The results showed that the RNN model is capable of performance prediction of the system with a high reliability and accuracy. This methodology provides a simple and effective approach in dynamic simulation of gas turbines, especially when real datasets are only available over a limited operational range and using simulated datasets for modelling and simulation purposes is unavoidable.

Besides, I applied open-loop and closed-loop NARX models to predict the dynamic behavior of a single shaft gas turbine. NARX models are subsets of artificial neural networks. NARX has a dynamic nature with exogenous inputs and may also be employed to predict the next value of the input signal or to filter noisy input signals. In a NARX model, there are feedback connections enclosing several layers of the network. A NARX network may be designed as a feedforward time-delay neural network (TDNN); without the feedback loop of delayed outputs, when dealing with time-series predictions. In this case, it can substantially reduce the predictive performance. To set up these models, datasets of important variables of the gas turbine were used for training, validation and test processes. For this purpose, comprehensive programing codes were developed in MATLAB and Python programming environments. In addition to the open-loop model, a closed-loop model was also set up for multi-step prediction.

For setting up a reliable NARX model with an acceptable accuracy, such as other recurrent neural networks, different structures were considered. These structures were on the base of different factors such as number and type of inputs and outputs, training algorithms, number of hidden layers, number of neurons in the hidden layer(s), type of activation functions, the maximum number of iterations, number of recurrent connections, and time delays in the recurrent connections. Besides, before making a decision about the NARX structure, some other vital information about the system dynamics, data types, and modelling objectives were collected.

The results proved that the NARX models are capable of performance prediction of the system with a high reliability and accuracy. The methodology developed in this research provides simple and effective approaches in black-box modelling of gas turbines, especially when real datasets are only available over a specific operational range, so that using simulated datasets for modelling and simulation purposes is unavoidable.

The results of these studies demonstrated the capability of the data-driven models in reliable prediction of gas turbines dynamic behavior over different operational ranges. These studies and methodologies may be applied to other industrial equipment.

II – PUBLICATION(S) DURING YOUR FELLOWSHIP

1- Recurrent Neural Network Based Simulation of a Single Shaft Gas Turbine, H. Asgari; E. Ory, J. Lappalainen, Proceedings of The 61st SIMS Conference on Simulation and Modelling SIMS 2020, Vol.176, issue14, p. 99-106, doi: https://doi.org/10.3384/ecp2017699

*** This paper was also presented at AI Day 2020*

2- Enhancing Technical Simulations with Machine Learning, H. Asgari; J. Kortelainen; M. Tahkola, ERCIM News, Issue 122, pp.16-17, URL: Enhancing Technical Simulations with Machine Learning — VTT's Research Information Portal

3- Machine Learning Approaches for Modelling a Single Shaft Gas Turbine, H. Asgari; E. Ory, International Journal of Modelling, Identification and Control (IJMIC), Accepted (Waiting for Publication)

4- Prediction of Dynamic Behavior of A Single Shaft Gas Turbine Using NARX Models, H. Asgari; E. Ory, Proceedings of the ASME Turbo Expo 2021: Turbomachinery Technical Conference and Exposition, Volume 6, June 7–11, 2021. doi: https://doi.org/10.1115/GT2021-58960

*** This paper was also submitted to AI Day 2021*

5- Linear and Nonlinear Black-Box Modelling of an Industrial Gas Turbine, H. Asgari; E. Ory, Full manuscript to be submitted (as a Journal article).

6- NARX Models for Dynamic Simulation of A Micro Gas Turbine, H. Asgari; E. Ory, to be submitted to ENTROPY Journal (Already received an invitation from the journal for a special issue: Physics-Based Machine and Deep Learning for PDE Models)

7- NARX Models for Gas Turbine Engines-A Review, H. Asgari; E. Ory, To be submitted to ASME TURBOEXPO 2022 (Abstract has been accepted)

III – ATTENDED SEMINARS, WORKHOPS, CONFERENCES

1. The 61st SIMS Conference on Simulation and Modelling SIMS 2020 (Virtual)
2. ASME Turbo Expo 2021: Turbomachinery Technical Conference and Exposition (Virtual)
3. *AI Day, Finland, 2020*
4. *AI Day, Finland 2021*

IV – RESEARCH EXCHANGE PROGRAMME (REP)

As Research Exchange Program (REP), I visited the following research centers, each for two weeks:

1. **Department of Computer Science at NTNU, Norway**
   During my stay at NTNU, I mainly engaged in exploring and developing Python codes for a hackathon (a mini car robot) using the PiCar-X. I tested the functionality of the codes and wrote documentation for the students participating in the hackathon competition.

2. **Fraunhofer Institute for algorithms and scientific computing (SCAI), Sankt Augustin, Germany**
   During my stay at SCAI, I became familiar with EVOLOPRO project. The project is part of the Fraunhofer initiative "Biological Transformation". Starting in 2019. . The main idea is to set up the required flexibility for a data-driven based model, so that the model can be applied to similar systems. I shared my ideas with SCAI researchers about the capability of applying the relevant methodology to industrial systems.