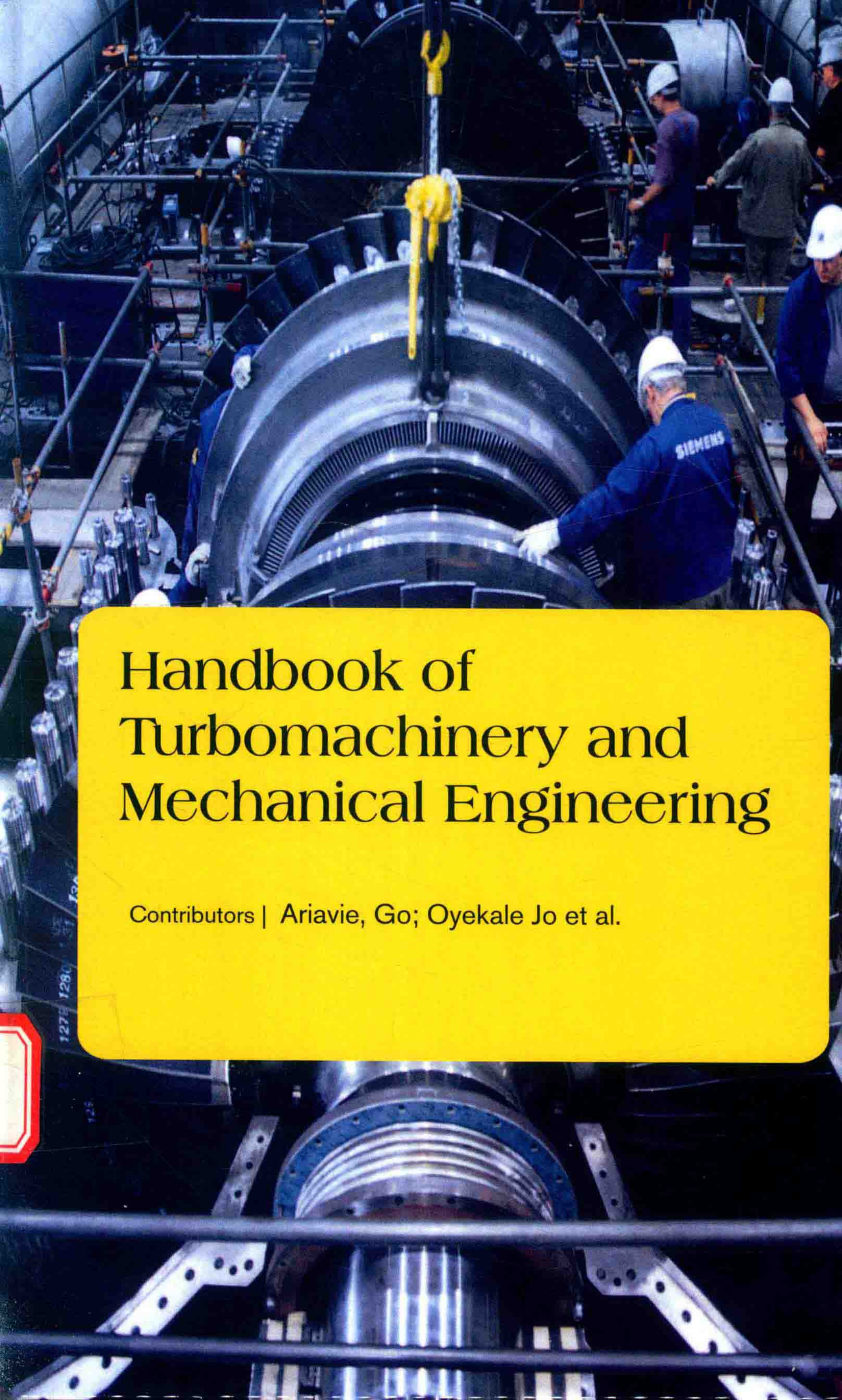


# Handbook of Turbomachinery and Mechanical Engineering

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# Handbook of Turbomachinery and Mechanical Engineering

# List of Abbreviations

| | |
|---|---|
| AIP | aerodynamic interface plane |
| AFTRF | Axial Flow Turbine Research Facility |
| CFD | Computational Fluid Dynamics |
| CFD | control and processing module"CPM |
| CMM | coordinate measuring machine |
| EO | engine order |
| FD | Finite Differences |
| FHP | Five-Hole Probes |
| FM | frequency modulated |
| GA | Genetic Algorithms |
| IGV | inlet guide vane |
| ITSM | Institute of Thermal Turbomachinery |
| IBRs | integrally bladed rotors |
| LOM | Largest of maximum |
| MCC | Measurement Computing Corporation |
| NL | nominal loading |
| NSMS | nonintrusive stress measurement systems, |
| NGV | nozzle guide vanes |
| OPR | once-per-revolution |
| RSS | root-sum-squared |
| RSI | Rotorstator interaction |
| SQP | Sequential Quadratic Programming |
| SA | Simulated Annealing |
| SOM | Smallest of maximum |
| TTL | transistor-transistor logic |
| FIS | Fuzzy Inference System |

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# Preface

The text *Handbook of Turbomachinery and Mechanical Engineering* presents new material on advances in fluid mechanics of turbomachinery, high-speed, rotating, and transient experiments, cooling challenges for constantly increasing gas temperatures, advanced experimental heat transfer and cooling effectiveness techniques, and propagation of wake and pressure disturbances. Performance modelling of steam turbine performance using fuzzy logic membership functions has been focused in first chapter. A study on fluid self-excited flutter and forced response of turbomachinery rotor blade has been presented in second chapter. Third chapter discusses some design systems for turbomachinery applications that have been developed over the years in order to assist the designer in finding the optimal geometry by making better use of the available information. In fourth chapter, the dynamic response analysis for circular disks with different dimensions and diskblades-disk structures have been carried out to better understand the fundamental dynamic behavior for the complex turbomachinery. Fifth chapter provides some empirical information for designing industrial centrifugal compressors with a focus on the impeller. The purpose of sixth chapter is to present and discuss a preliminary and simple method to extend the currently available design maps into the small scale range ($Re < 10^5$) by introducing in the Balje charts an efficiency correction that depends on the specific speed $n_s$. Numerical analysis of horizontal-axis wind turbine characteristics in yawed conditions has been presented in seventh chapter. In eight chapter, a novel approach to simulating laminar to turbulent transition is described that can be implemented into a general RANS environment. Ninth chapter focuses on time efficient adaptive gridding approach and improved calibrations in five-hole probe measurements. Tenth chapter explains the particular data processing methods used to identify rotor vibration. Experimental investigation of factors influencing operating rotor tip clearance in multistage compressors has been performed in eleventh chapter. A miniature four-hole probe with minimum spatial error has been designed and fabricated in last chapter.

# Contents

# Chapter 1

## PERFORMANCE MODELLING OF STEAM TURBINE PERFORMANCE USING FUZZY LOGIC MEMBERSHIP FUNCTIONS

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## ABSTRACT

A Fuzzy Inference System for predicting the performance of steam turbine based on Rankine cycle is developed using a 144-rule based in analyzing the generated data for different inlet and outlet conditions. The result of efficiency for different types of membership functions and defuzzification method was obtained. Centroid method of defuzzification gave good results irrespective of the type of membership function with error less than 5%. However, other defuzzification methods gave good result for some types of membership functions. Result of different input data tested do not vary significantly (P<

## INTRODUCTION

Performance prediction tends to estimate useful parameters such as efficiency based on certain input parameters (Benner, Sjolander, and Moustapha, 2006a, Benner, Sjolander, and Moustapha, 2006b, Benner, Sjolander, and Moustapha, 2004, Dunham and Came, 1970, Živković, 2000). Steam turbine is mostly used for generating mechanical energy due to its advanced features and outstanding qualities (Mathis, 2003). Currently, researchers are working assiduously towards improving efficiency of steam turbine by developing better metallurgical materials that can withstand steam at temperature as high as 6000C and beyond critical pressure (Brooks,2012). However, not much improvement on its efficiency has been observed in recent times, due to the long technological history of efficiency of turbine cycles being about 52%, which is about 30% higher than that of a simple gas cycle, and about 40% as reported by General Electric (Organoski, 1990). One challenge faced by end-users is turbine operating at off-design conditions almost throughout its life, therefore, manufacturers need to accurately predict performance at varying operating conditions and incorporate a control system performance monitoring. Performance prediction has graduated from qualitative guess checks to several empirical, analytical and numerical methods. Empirical methods suitable for gas turbines (Ainley and Mathieson, 1951, Dunham and Came, 1970, and Craig and Cox, 1971) can be modified with suitable correlations for non-condensing steam turbine modeling (Denton, 1993). However, Dixon (2005) argued that the empirical methods lack first principle in their derivations, and he developed a model that cannot be implemented because it requires quantifying all losses which is practically impossible. Existing analytical methods in standard literature (Horlock and Denton, 2003) come with rigorous mathematical complexities and require requisite knowledge of turbo-machinery physics for their application. There are well developed numerical methods such as Computational Fluid Dynamics (CFD), but they are very expensive and time consuming. Besides, their results are not accurate as reported by Denton (Emami, 1997). Current market trend of steam turbines has necessitated the development of easy to use performance prediction methods that give good result. Methods that do not require mathematical formulation such as Fuzzy logic, genetic algorithm and artificial neural network are therefore good alternatives.

Fuzzy Logic is one of the best methods that do not require mathematical formulation. It replaces rigorous, mathematical formulations with ambiguous qualitative and random conceptions (Ariavie, Ovuworie and Ariavie, 2011). It is easy to use and has been applied to various systems ranging from linear to high level non-linear systems. Fuzzy logic tends to map a set of inputs to a set of outputs, obeying a list of rules (combination of statements with inference). The rules are formed from the variables (members of input and output sets) and the adjectives that describe those variables (membership functions). Before one can build a system that interprets rules, it is imperative to define all the terms to be used and the adjectives that describe them. To say that the pressure is high, one needs to define the range that the steam pressure can be expected to vary as well as what is implied by the word high (Harris, 2006). Due to its advantages and wide applicability, the method has gained much development and is discussed in detail as a subject in standard literature (Cox, 1994, Perfilieva and Mockr, 1999, Sivanandam et al., 2001, Yager and Filer,1994, Micheal and Shapiro, 2006). This work investigated the application of Fuzzy Logic to performance prediction of steam turbine. A Fuzzy Inference System (FIS) was developed. The FIS can be used to determine the thermodynamic efficiency of a steam turbine from the steam inlet pressure, inlet temperature and exit pressure as input variables. The FIS was trained with analyzed data generated from developed MATLAB simulation code that estimates efficiency, back work ratio and specific steam consumption based on the Rankine Cycle. The effect of different types of membership functions and defuzzification methods available in the MTALB FIS development environment was investigated and compared to the analytical result.

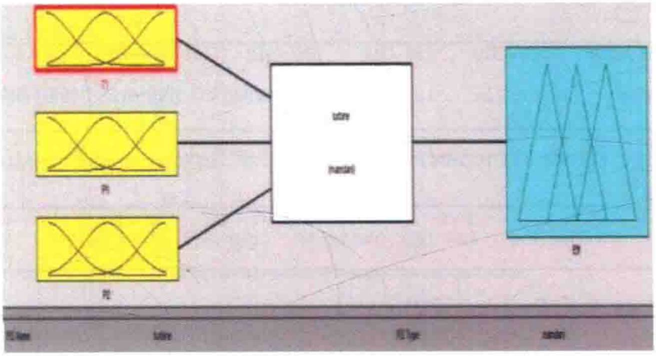

**Figure .1:** Mandini Fuzzy Inference System for Performance Prediction of Steam Turbine

## METHODS AND MATERIALS

Data was generated using Matlab simulation code for steam turbine modeling; however some suitable assumptions were made. The data was analyzed, filtered and then used to train the fuzzy inference systems developed for steam turbine performance predictions. MATLAB Simulation program based on the Rankine combine cycle for steam turbine modeling was developed. Basic assumptions for applying the Rankine cycle to steam turbine modeling given in standard literature (Celgel, and Boles,2006, Potter and Somerton, 2004) were made. Optimum reheat temperature of one-fourth inlet conditions (Celgel, and Boles, 2006) was adopted, and varying conditions were adopted for the regenerative cycle. Turbine and pump isentropic efficiency were taken as 85%. The code was used to simulate result for varying turbine conditions. The data was analyzed in order to ascertain the rules for the fuzzy inference system. Turbine inlet and outlet conditions (pressure and temperature), and their effects on the turbine efficiency were investigated. Development of Fuzzy Inference System: The Mandini type of Fuzzy Inference System was adopted for this work. The turbine inlet conditions (Boiler pressure (P1) and temperature (T1) respectively) and the turbine exit pressure (Condenser pressure (P2) ) were taken as the three inputs variables while the efficiency of the turbine was taken as the output of the Fuzzy Inference System (FIS) for performance prediction of steam turbine. This is shown in figure

The membership functions for each variable was designed with the following range of values as seen best for developing rules for the turbine based on the data analyzed.

**Table 1:** Range Values of membership function for Turbine inlet temperature (T1)

| Values in degree Celsius | 100 – 320 | 250 – 400 | 320 – 450 | 400 – 500 | 450 – 600 |
|---|---|---|---|---|---|
| Designation | Very Low (VL) | Low (L) | Medium (M) | High (H) | Very High (VH) |

**Table 2:** Range Values of membership function for Turbine Inlet Pressure (P1)

| Values in MPa | 1 – 4 | 2 – 8 | 5 – 12 | 7 – 18 | 12 – 20 | 16 – 24 |
|---|---|---|---|---|---|---|
| Designation | Very Low (VL) | Low (L) | Medium (M) | High (H) | Very High (VH) | Very High (VVH) |

**Table 3:** Turbine Exit Pressure (P2)

| Values in MPa | 0.0015 – 0.015 | 0.01 – 0.05 | 0.04 – 0.1 | 0.08 – 0.5 | 0.3 – 1.2 |
|---|---|---|---|---|---|
| Designation | Very Low (VL) | Low (L) | Medium (M) | High (H) | Very High (VH) |

**Table .4:** Range Values of membership function for Efficiency

| Values | -0.2 – 0.2 | 0 – 0. 4 | 0.2 – 0.6 | 0.4 – 0.8 | 0.6 – 1.0 |
|---|---|---|---|---|---|
| Designation | Very Low (VL) | Low (L) | Medium (M) | High (H) | Very High (VH) |

Four (4) different membership functions which includes the triangular (trimf), Gaussian (gausmf), Polynomial (Pmf) and the modified Gaussian (Gauss2mf) were tested with each generating its unique curve based on the function it describes. Their default parameters for each of the curves were adopted. The output (Efficiency) for each selected membership function was recorded. A sample dialog box for editing the type membership function and its parameters is shown in figure 2.2.

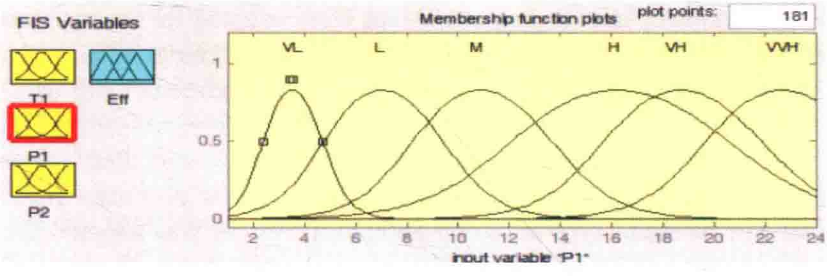


**Figure 2:** The Polynomial membership function (Pmf) for the Inlet temperature (T1)

Five (5) different defuzzification methods (the Centroid, Bisector of Area (BOA), Middle of maximum (MOM), Largest of maximum (LOM) and Smallest of maximum (SOM)) were also tested and corresponding values of efficiencies recorded. They include One hundred and forty four (144) rules were selected based on analysis of the generated data and a few is shown in figures 2.3 and 2.4, while Figures 2.5, 2.6, 2.7 and 2.8 shows the surface plots representing the rules. The minimum values and maximum values were used for the 'and' and 'or' combination respectively. The FIS developed was tested with the data below.

**Table 2.5:** Test data for fuzzy inference system

| T1 | P1 | P2 | Efficiency |
|---|---|---|---|
| 360 | 4 | 0.05 | 0.371 |
| 600 | 24 | 0.02 | 0.502 |

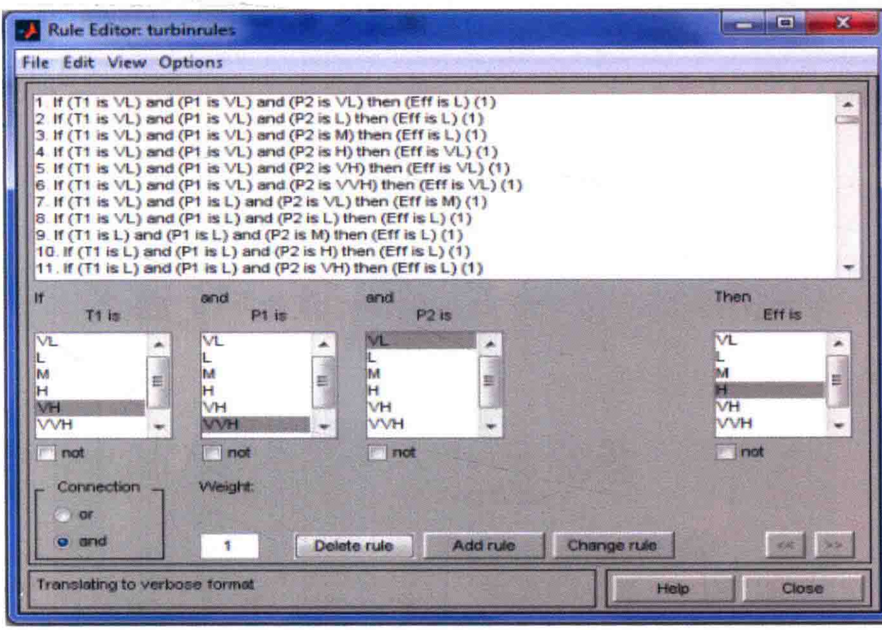


Figure. 3:

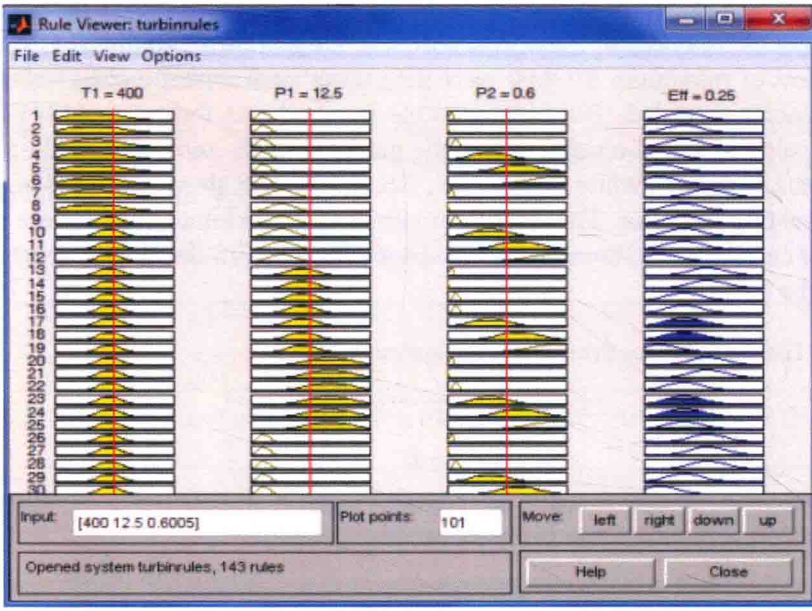


Figure.4:

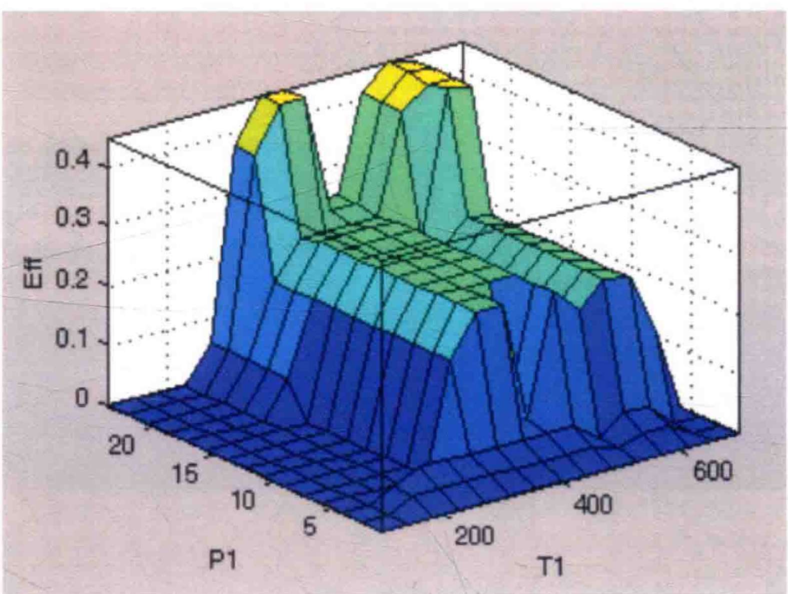


Figure.5: