Fuzzy Approach Applied in Fault Detection and Isolation to the Compression System Control

Ahmed Hafaifa[1], Ferhat Laaouad[2], Kouider Laroussi[1]

[1] Dep. Industrial Processes Automation,
Science and Technology Faculty,
University of Djelfa,
17000 DZ Algeria,
hafaifa@hotmail.com, kouider-laro@hotmail.com

[2] Department of Industrial Process Automation,
Faculty of Hydrocarbons and Chemistry,
University of Boumerdes,
35000 DZ, Algeria.
ferhatlaaouad@umbb.dz

Abstract: During the last decade, significant change of direction in the development of control theory and its application has attracted great attention from the academic and industrial communities. The concept of "Intelligent supervision "has been suggested as an alternative approach to conventional supervision techniques for complex control systems. The objective is to introduce new mechanisms permitting a more flexible supervision system, but especially more robust one, able to deal with model uncertainties and parameter variations. In this work, we present an application of the fuzzy approach in fault detection and isolation of surge in this compression system. This paper illustrates an alternative implementation to the compression systems supervision task using the basic principles of model-based fault detection and isolation associated with fuzzy modelling approach. Application results of a fault detection and isolation for a compression system are provided, which illustrate the relevance of the proposed fuzzy fault detection and isolation method.

Keywords: Fault detection and isolation; Nonlinear systems; Fuzzy logic; Fuzzy fault detection and isolation; Compression system; Centrifugal compressor; Surge phenomena.

1. Introduction

Today the compression systems are subjected to highly hostile working conditions. The manufacturer is greatly interested with any improvement in performance, life and weight reduction without loss of reliability [11]. Therefore, it is worthwhile to carefully estimate the reliability of rotating systems in order to improve the supervision and the control system or eventually modify the design. Reliability analyses of the supervision structure require some information on the model of the compression system. We know it is difficult to obtain the mathematical model for a complicated mechanical structure. The turbo compressor is considered as a complex system where many modelling and controlling efforts have been made. In the regard to the complexity and the strong non linearity of the turbo compressor dynamics, and the attempt to find a simple model structure which can capture in some appropriate sense the key of the dynamical properties of the physical plant, we propose to study the application possibilities of the recent supervision approaches and evaluate their contribution in the practical and theoretical fields consequently.

In the literature, numerous applications of faultdiagnosis are reported for many manufacturing industries. For the last two decades, there have been extensive research efforts on developing model-based FDI techniques [3],[15],[23]. A residual signal is generated by comparing the measured output signal and the estimated one from a nominal system model. After being processed, this residual can be used as the indicator of abnormal behavior (faults) of the system. More advanced methods are data-driven process monitoring methods [2], [14], most heavily used in many industrials applications. Other methods rely on analytical redundancy [6], [12], the comparison of the actual plant behaviour to that expected on the basis of a mathematical model. Sometimes, further insight is required as to the explicit behavior of the model involved and it is here that fuzzy and even neuron fuzzy methods come into their own in fault diagnosis applications [12]. Other authors have used evolutionary programming tools to design observers and neural networks. The work on fault diagnosis

Artificial Intelligence community was initially focused on the expert system or knowledge based approaches [14], where heuristics are applied to explicitly associate symptoms with fault hypothesis. The short comings of a pure expert system approach led to the development of model-based approaches based on qualitative models in form of qualitative differential equations, signed diagraphs, qualitative functional and structural models, etc ., [16],[19],[20].

Facing to the studied industrial process complexity, we choose to make recourse to fuzzy logic for analysis and treatment of its supervision problem owing to the fact that these technique constitute the only framework in which the types of imperfect knowledge can jointly be treated (uncertainties, inaccuracies, ...) offering suitable tools to characterise them. This choice is motivated by the effectiveness of fuzzy logic solution for many industry problems [5], [14], [15]. Indeed, based only on human expert knowledge, fuzzy logic solutions are very powerful on nonlinear systems modelling and control.

This work illustrates an alternative implementation to the compression systems supervision task using the basic principles of model-based fault detection and isolation associated with the self-tuning of surge measurements with subsequent appropriate corrective actions. Using a combination of fuzzy modelling approach makes it possible to devise a fault-isolation scheme based on the given incidence matrix.

The presented approach is based on the use of the fuzzy model. As was introduced in [3], [15], by applying a Takagi-Sugeno- type fuzzy model with interval parameters, one is able to approximate the upper and lower boundaries of the domain of functions that result from an uncertain system.

The fuzzy model is therefore intended for robust modelling purposes; on the other hand, studies show it can be used in fault detection as well. The novelty lies in defining of confidence bands over finite sets of input and output measurements in which the effects of unknown process inputs are already included. Moreover, it will be shown that by data pre-processing the fuzzy model parameter-optimization problem will be significantly reduced. By calculating the normalized distance of the system output from the boundary model outputs, a numerical fault measure is obtained. The main idea of the proposed approach is to use the fuzzy model in an FDI system as residual generators, and combine the fuzzy model outputs for the purpose of fault isolation. Due to data pre-processing, the decision stage is robust to the effects of system disturbances.

The paper presents an application of the fuzzy model in fault detection and isolation for the compression system with interval type uncertain parameters. The FDI problem was split into two steps. In the former step the fuzzy model along with data pre-processing and low-pass filtering were introduced into the fault detection scheme. In the latter the combination of residuals was used in the fault-isolation stage. In its final part the paper gives some conclusions about this application.

2. Surge of Centrifugal Compressor

Centrifugal compressors will surge when forward flow through the compressor can no longer be maintained, due to an increase in pressure across the compressor, and a momentary flow reversal occurs. Once surge occurs, the reversal of flow reduces the discharge pressure or increases the suction pressure, thus allowing forward flow to resume again until the pressure rise again reaches the surge point. Surge is characterized by large amplitude fluctuations of the pressure and by unsteady, but circumferentially uniform, annulus-averaged mass flow. This essentially one dimensional instability affects the compression system as a whole and results in a limit cycle oscillation in the compressor map.

This surge cycle will continue until some change is made in the process or compressor conditions. Figure 1 shows a pressure trace for a compressor system, which was initially operated in a steady operating point. By throttling the compressor mass flow, the machine is run into surge. This figure illustrates the difference between pressure variations before and after surge initiation. A surge controller typically measures a function of pressure rise versus flow. The controller operates a surge valve to maintain sufficient forward flow to prevent surge [10], [11], [17].

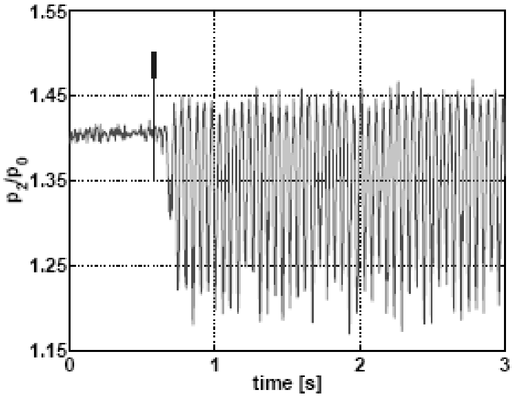

Figure. 1. Surge initiation in centrifugal compressor

Surge initiation measurements are performed to determine the stability of the compressor system. The initiation of surge is defined as the point at which the amplitude of the pressure trace starts to grow and a distinct oscillation frequency appears which is pointed out in the lower right plot. Upon surge initiation a surge development is recognized in which the surge develops to fully developed surge that occurs. Due to a constant shaft power, the reduction of mass flow results in a slight increase of the mean rotational speed.

Surge supervisory system

The transfer of gas along a pipeline is a common process in the oil, chemical and petro-chemical industries. For cost-effectiveness, gas is usually transported at high pressure via a compressor before entering the pipeline. The compressor efficiency is maximised when the flow rate through it is kept low and the pressure high, with the minimum possible flow rate being restricted by the risk of compressor entering surge condition.

The surge phenomena is an unstable and undesirable operating condition of the compressor, occurring when the flow through it is reduced to the point where the compressor discharge pressure is less than the line pressure. This causes a momentary flow reversal, reducing line pressure and causing erratic flow output. With the reduced line pressure, flow through the compressor is re-established, causing line pressure to increase and the cycle to begin again. If the factors leading to the surge condition are not correctly and quickly rectified, the output will continue to oscillate resulting in damage to the compressor. The surge supervisory system offers:

- Protection against compressor damage such as bent shafts, cracked or ruptured castings, damaged impeller and bearings
- Reduction in compressor downtime and productivity costs.
- Savings on maintenance costs.

Although all surge supervisory system techniques are based on a similar concept - to maintain a minimal flow at extreme conditions - surge supervisory system with fuzzy fault detection and isolation achieves this with a robust and efficient supervision module offering configuration and operator interface flexibility. If and when required by the process, the supervision module takes into account the following [10], [18] and [22]:

1. Location of the flow measurement
2. Type of compressor (axial, reciprocating or centrifugal)
3. Type of operating speed (constant or variable)
4. Value of discharge and suction pressures
5. Value of inlet temperature
6. Value of the compression ratio
7. Composition of the transported gas (density, specific heat, molecular weight)
8. Characteristics of all valves used in the control process

Fuzzy fault detection and isolation method defining the surge point over a wide range of changing conditions makes it possible to set the control line for optimum surge protection without unnecessary re-cycling. This method automatically compensates for changes in pressure rise, mass flow, temperature, and compressor rotor speed. The system utilizes a characterization of compression ratio versus compensated compressor inlet flow function as control parameters. This algorithm allows for use of the surge control system in this paper, resulting in minimized recycle or blow-off flow. This method reduces the initial cost and simplifies engineering, testing, operation, and maintenance associated with the system when compared to alternative methods [23]. The input signals required to facilitate use of the surge control algorithm on centrifugal compressors are the suction flow differential pressure, suction pressure and discharge pressure as indicated in Figure 2.

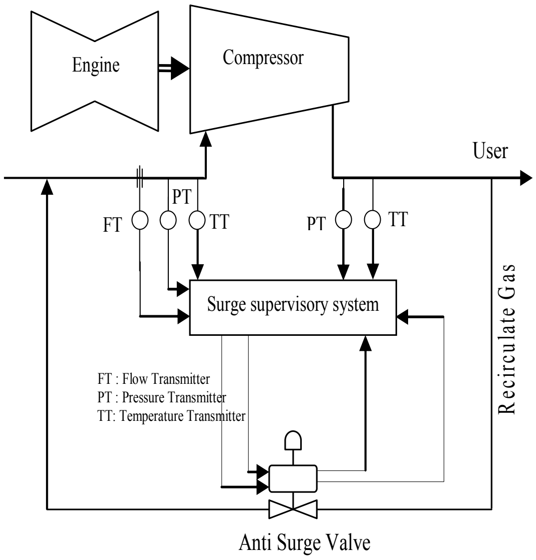

Figure. 2. Compression System

Using the fuzzy logic model it was possible to analyze the deficiencies of the original surge control algorithm by observing the "real" surge margin calculated from the compressor performance, the objective of an anti-surge controller should not be limited to basic independent machine protection. The anti-surge control performance as an integral part of the machine performance control must be considered. Storing real surge points, applying fuzzy logic control of the recycle valve (variable gain depending on operating region) and compensating for interaction between surges, overload and process control can significantly expand the operating window. This allows operation very close to the actual surge lines (4-8%) under all process conditions. Straight line surge control, even with variable slope, must make allowance for the poor fit to actual surge points by using a wider margin (15-20%).

Interim remedial actions to improve the surge control constants were carried out until an advanced complex control system was installed. An identical steady-state model that was built separately helped to design and test the revised compressor surge control algorithm prior to commissioning on the compressor [12].

3. The Compression System Model

Over fifteen years ago, Moore and Greitzer developed a phenomenological model for rotating stall and surge [10]. This pioneering work modeled the compression system with just three components:

- The first component is the inlet duct that allows infinitesimally small disturbances at the duct entrance to grow until they reach an appreciable magnitude at the compressor face.
- The second component is the compressor itself, modeled as an actuator disk, which raises the pressure ratio by doing work on the fluid.
- The third component is the plenum chamber (or diffuser) downstream, which acts as a large reservoir and responds to fluctuations in mass flow with fluctuations in pressure behind the actuator disk.

In this paper, we are considering a compression system consisting of a centrifugal compressor, close coupled valve, compressor duct, plenum volume and a throttle. The throttle can be regarded as a simplified model of a turbine [2], [10]. The model to be used for controller design is in the form:

$$\left\{\begin{aligned} \dot{P}_p &= \frac{k\,P_{01}}{\rho_{01}\,V_p}\left(m - k_t\sqrt{P_p - P_{01}}\right) \\ \dot{m} &= \frac{A_1}{L_c}\left[P_{01}\left(1+\eta_i\,(m,N)\frac{\Delta h_{ideal}}{C_p\,T_{01}}\right)^{\frac{4(k-1)}{k}} - P_p\right] \\ \dot{N} &= \frac{1}{2J\pi}\left(\frac{\eta_t\,m_{tur}\,C_{p,t}\,\Delta T_{tur}}{2\pi N} - 2\,r_{22}\,\sigma\,\pi\,N\left|m\right|\right) \end{aligned}\right. \qquad (1)$$

Where p_p is the plenum pressure, K is a numerical constant, p_{01} is the ambient pressure, ρ_{01} is the inlet stagnation density, V_P is the plenum volume, m is the compressor mass flow, k_t is a parameter proportional to throttle opening , A_1 is the area of the impeller eye (used as reference area), L_c is the length of compressor and duct, η_i is the isentropic efficiency, N is the spool moment of inertia, Δh_{ideal} is the total specific enthalpy delivered to fluid, c_p is the specific heat capacity at constant pressure, c_v is the specific heat capacity at constant volume, T_{01} is the inlet stagnation temperature and k is the ratio of specific heats $k = \frac{c_p}{c_v}$.

The Moore-Greitzer model gives rise to three ordinary differential equations, the first for the non-dimensional total-to-static pressure rise Δp across the compression system, the second for the amplitude of mass flow rate fluctuations m, and the third for the non-dimensional, spool moment of inertia. In the above equations, γ is a characteristic function of the compression system, for each compressor characteristic the constants σ and β are determined from measurements. The quantity ϕ_T determines how much mass will be removed in a user-controlled fashion through a bleed valve. It may be written as [11]:

$$\phi_T = \gamma\sqrt{\Delta P} \tag{2}$$

The functional form between ϕ and ψ is simply the performance map and is often approximated by [10], [11]:

$$\psi = a + b\phi + c\phi^2 + d\phi^3 \tag{3}$$

Where a, b, c, and d are constants which must be determined by a curve fit of the experimental data. The most important approximations underlying the Moore-Greitzer model are that (i) it is valid under small perturbations m, and, (ii) the time scale of the dynamics governing m is much faster than the time scale of the dynamics governing ϕ.

The present work has analytically integrated the right hand side of equation (1). This integration does not require a priori assumptions about the analytical form of the performance map [9], [10], [13]. Note that the Moore-Greitzer model does not attempt to explain what physical mechanism triggers these instabilities. Rather, it attempts to determine the favorable conditions under which the disturbances will grow, and what can be done to suppress the instabilities. Its simplicity, mathematical elegance, and generality have led to wide acceptance and use of this model by researchers in industry, government and academia. It is also used in surge control research with the belief that rotating stall is a precursor to surge, and with the expectation that elimination of rotating stall will also eliminate the development of surge.

The instabilities within compression systems can be studied using energy considerations. As shown by Gysling and Greitzer [10] the rate of energy input by the compressor to the fluid (over and above the steady state input) may be written as:

$$\delta E = \int_{Annulus} \delta(\Delta P)\delta\phi dA \tag{4}$$

If this integral is positive, energy is added to the fluid by the compressor, and the disturbances will grow in amplitude. In the performance map of the compression systems, the slope of the curve is negative to the right side of the peak. In this region, a small increase in mass flow rate $\delta\phi$ will decrease pressure, so that $\delta(\Delta p)$ is negative.

Fuzzy models

Fuzzy models are flexible mathematical structures that, in analogy to nonlinear models, have been recognized as universal function approximators [8], [21]. Fuzzy models use 'If-Then' rules and logical connectives to establish relations between the variables defined for the model of the system. For the given example, let the system to model be the relation between surge and the fluctuations in the mass flow coefficient $\Delta\Phi$ and pressure coefficient $\Delta\Psi$. Thus, in fuzzy modeling the fuzzy 'If- Then' rules take the form:

If u is surge then y is High (5)

The fuzzy sets in the rules serve as an interface amongst qualitative variables in the model, and the input and output numerical variables. The fuzzy modeling approach has several advantages when compared to other nonlinear modeling techniques, in general, fuzzy models can provide a more transparent representation of the system under study, maintaining a high degree of accuracy.

Takagi and Sugeno [1], [4], [5] introduced a fuzzy rule-based model that can approximate a large number of nonlinear systems. The Takagi-Sugeno (TS) fuzzy model consists of representing the base rules as follows:

$$R_i : \text{IF u is } A_i \text{ THEN } y = f_i(u), i = 1, \ldots, K \tag{6}$$

Where R_i denotes the ith rule, K is the number of rules, u is the antecedent variable, y is the consequent variable and A_i is the antecedent fuzzy set of the *i*th rule. Each rule *i* has a different function f_i yielding a different value for the output y_i. The most simple and widely used function is the affine linear form :

$$R_i \ : \text{IF u is } A_i \text{ THEN } y = a_i^T u + b_i \ , i = 1,\ldots, K \quad (7)$$

Where *ai* is a parameter vector and *bi* is a scalar offset.

Fuzzy model of compression system

The fuzzy logic model is a rule-based system that receives information fed back from the plant's operating, in this case the normalized fluctuations of Φ and Ψ. These crisp values are fuzzified and processed using the fuzzy knowledge base. The fuzzy output is defuzzified in throttle and CCV gains in order to control the plants operating conditions.

A fuzzy system involves identifying fuzzy inputs and outputs, creating fuzzy membership functions for each, constructing a rule base, and then deciding what action will be carried out. The response of the system is used to model the control system. Increasing either the throttle gain γ_T or CCV gain γ_V will stabilize the system with a penalty of pressure lost across the plenum. The fluctuations of the mass flow coefficient $\Delta\Phi$ and pressure coefficient $\Delta\Psi$ are normalized before being sent to the fuzzy model as the crisp input by the following:

$$\Delta\Psi_i = \frac{\left|\Psi_i - \Psi_{i+\Delta t}\right|}{Max\,(\Psi_i , \Psi_{i+\Delta t})} \quad (8)$$

$$\Delta\Phi_i = \frac{\left|\Phi_i - \Phi_{i+\Delta t}\right|}{Max\,(\Phi_i , \Phi_{i+\Delta t})} \quad (9)$$

Samples of the coefficients are taken at regular time-step intervals, $\Delta t = kh$ where k is a constant and h is the Runge-Kutta time step size. The crisp output from the fuzzy model adjusts both control gains by the following :

$$\gamma_{i+\Delta t} = \gamma_i + \gamma_i \Delta\gamma_i \quad (10)$$

Three steps are taken to create a fuzzy controlled compression system:

- Fuzzification (Using membership functions to graphically describe a situation)
- Rule evaluation (Application of fuzzy rules)
- Defuzzification (Obtaining the crisp results)

Step 1

First of all, the different levels of output (the throttle opening, the pressure coefficient and the mass flow coefficient) of the compression system are defined by the triangle membership functions for the fuzzy sets. The graph of the function shown below figures 3.a, b and c.

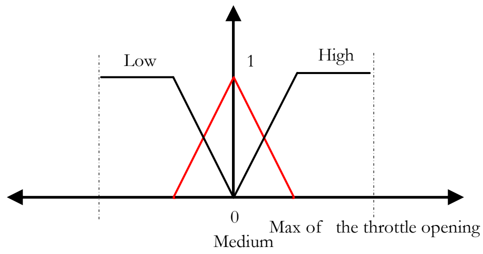

Figure 3.a. The membership functions of the throttle opening

Similarly, for the different Pressure coefficient variable:

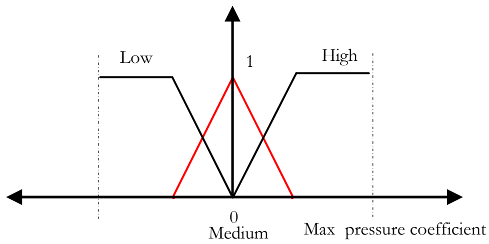

Figure 3.b. The membership functions of the pressure coefficient

The mass flow coefficient is also defined:

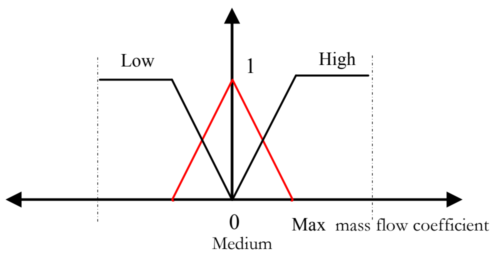

Figure 3.c. The membership functions of the mass flow coefficient

Step 2

The next step is to define the fuzzy rules. The fuzzy rules are merely a series of if-then statements as mentioned above. These statements are usually derived by an expert to achieve optimum results. For the case of two inputs and one output, the rule base is constructed by creating a matrix of options and solutions.

The matrix has the input variable along the top side. The entries in the matrix are the desired response of the system, the changes in either throttle or CCV gain. The rule base of three rules can be created:

1. If [$\Delta\Psi$ is Low] or [$\Delta\Phi$ is Low] Then [$\Delta\gamma_V$ and $\Delta\gamma_T$ is Low]
2. If [$\Delta\Psi$ is Medium] or [$\Delta\Phi$ is Medium] Then [$\Delta\gamma_V$ and $\Delta\gamma_T$ is Medium]
3. If [$\Delta\Psi$ is High] or [$\Delta\Phi$ is High] Then [$\Delta\gamma_V$ and $\Delta\gamma_T$ is High]

An application of these rules is shown using specific values for pressure coefficient and the mass flow coefficient. The values are seen in the following figures 4.a and b.

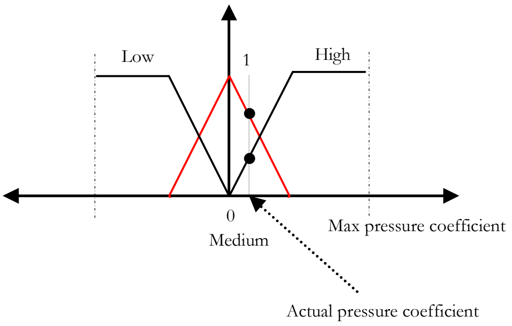

Figure 4.a. The actual pressure coefficient value

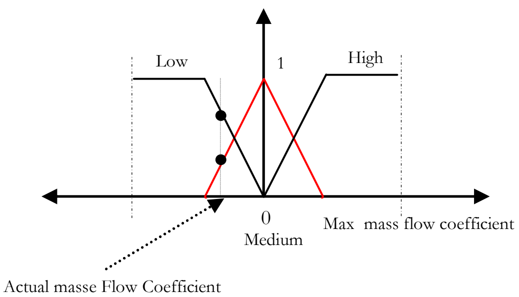

Figure 4.b. The actual masse flow coefficient value

The actual value belongs to the fuzzy set zero to a degree of 0.75 for "Pressure coefficient" and 0.4 for "Mass flow coefficient ". Hence, since this is an AND operation, the minimum criterion is used , and the fuzzy set approximately zero of the variable " The throttle opening " is 0.4 , this situation is illustrated in the figure below figure 4.c.

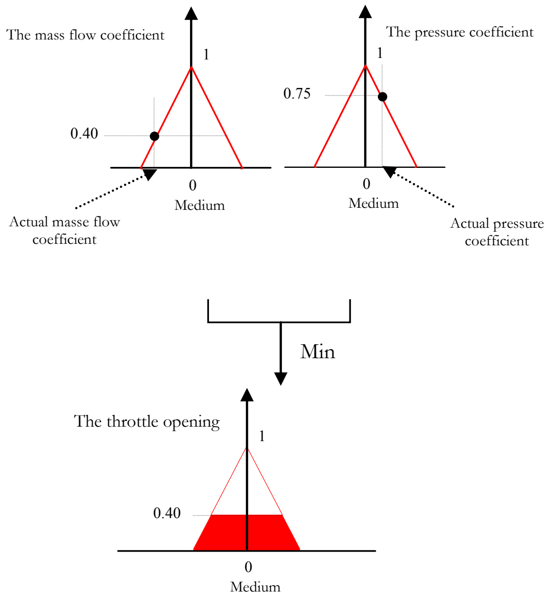

Figure 4. c. The satiation of the throttle opening

The following figure 6.d, show the result of the situations of the throttle opening yielded by the fuzzy rules (1, 2 and 3).

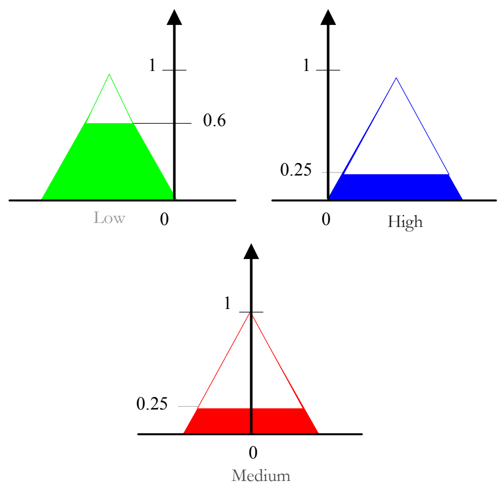

Figure 4.d. The different situations of the throttle

The four results are overlaps and is reduced to the following figure 6.e.

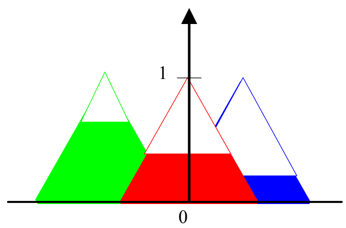

Figure 4.e. The result

Step 3

The result of the fuzzy controller so far is a fuzzy set (of the throttle opening). To choose an appropriate representative value as the final output (crisp values), defuzzification must be done. This can be done in many ways, but the most common method used is the centre of gravity of the set as shown below figure 5.

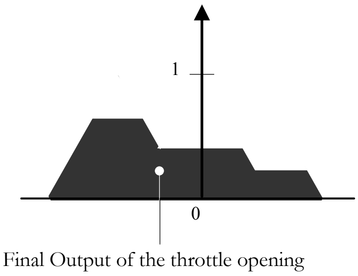

Figure 5. The final output determined by the centre of gravity method

Before implementing the fuzzy logic compensator in the compression system, a mathematical model was used to simulate the continuously operated compression system under Matlab / Simulink. The same model has been used to design the fuzzy logic controller. The simulation model corresponds to a single zone.

The experimental data of this work presents results from previous tests and background studies; a review of published materials, and recent laboratory tests funded by the Department of Automatic Control, of the University of Djelfa, Algeria, in collaboration with the station of the gas compression of SONATRACH Algeria. Previous tests and the most recently available measured surge internal flow data is parameterized to help identify factors that affect the indications that a compressor is approaching surge.

4. Application Results

The results of tows simulations are presented in this section to validate the robustness of the presented approach. The first is the results of simulations of the compression system in surge, and the second simulation is the compression system with control of surge using fuzzy fault detection and isolation method. The response of the masse flow aspiration with the compression system in surge can be seen in figure 6.

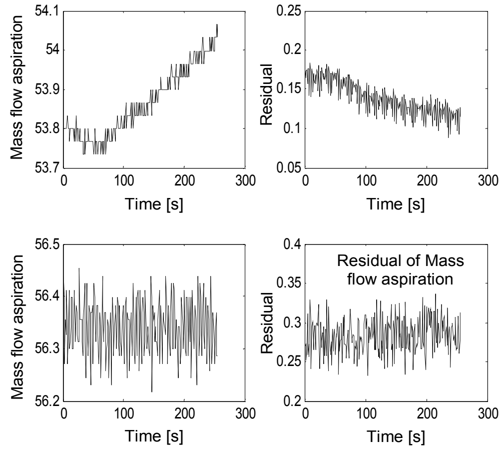

Figure 6. Input gas flow of the compression system

The response of the compression system with control of surge using fuzzy fault detection and isolation for the masse flow aspiration is shown in figure 7.

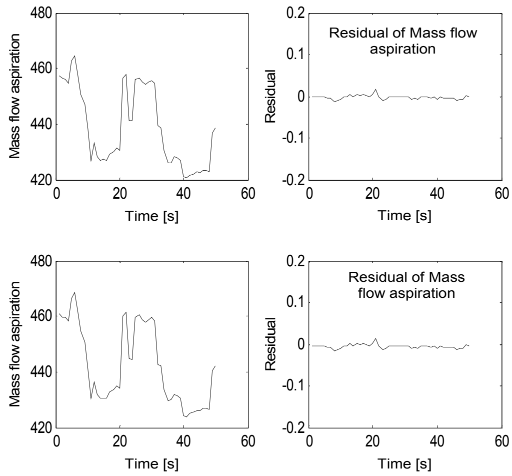

Figure 7. Input gas flow of the compression system

The same results for the Mass flow downstream, pressure aspiration and the pressure downstream are studied.

Fuzzy fault and detection of different complexities were studied for the most concerned parameters in this case of study (Mass flow aspiration, Mass flow downstream, pressure aspiration and the pressure downstream); the larger the computational time but also the better the results. A model FDI controller with a longer prediction horizon and a small control weighting factor provides good performance in terms of surge detection and isolation and reduced error. However, the observation on the variation of the controller output provided an interesting result. The implementation of a fuzzy logic controller on a real-time system promises robust control of the compression system, the fuzzy logic controller achieves the most robust control performance based on the logical understanding of the system behavior requiring no mathematical modeling of the underlying controlled system, which is tied to an operating range and subject to modeling errors due to simplified approximations or online/offline statistical modeling errors.

5. Conclusion

According to the above study, we can notice that the obtained compressor model is still complex and very difficult to manipulate, even it gives satisfactory results and even identical to reality. Consequently, it will be necessary to write a much simpler model that we can easily manipulate for fault detection and isolation purposes. A fault modeling strategy is proposed that is able to model a large class of faults by a limited number of fault models, which correspond to the extreme values of the considered faults. Identification of faults is performed by estimating the weights of the models in a model set designed with the proposed fault modeling method, in a multiple model framework. The advantage of this framework is the used of fuzzy logic method, a recent method that satisfies the requirements sited above. Although the compression system inheres a narrow operating range with a bandwidth around 14 Hz, the fuzzy controller can even drive the centrifugal compressor to oscillate up to 20 Hz with satisfactory tracking performance in the surge control.

This research result may be applied to various compression systems. In addition, due to its simplicity, this method is very adequate and practical for the study of complex nonlinear systems. The great benefit of this fuzzy logic approach is that the controller does not require the knowledge of the compressor map in order to find a desired equilibrium point. As well the same model can operate under active and passive surge control without the knowledge of which method is being implemented. The decision making is based solely on the compression system output, allowing the fuzzy model to be easily adapted to any turbo compressor system.

REFERENCES

1. ABID, H., M. CHTOUROU, A. TOUMI, **Robust Fuzzy Sliding Mode Controller for Discrete Nonlinear Systems,** International Journal of Computers, Communications & Control, Agora University Editing House - CCC Publications, vol. 3(1), 2008, pp. 6-20.
2. ALBERTSON, F., H. BODÉN, J. GILBERT, **Comparison of Different Methods to Couple Nonlinear Source Descriptions in the Time Domain to Linear System Descriptions in the Frequency Domain-Application to a Simple Valveless One-cylinder Cold Engine,** Journal of Sound and Vibration, Elsevier, vol. 291(3-5), 2006, pp. 963-985.
3. HOLLOWAY, A., L. E. HOLLOWAY, **Automated Control, Observation, and Diagnosis of Multi-layer Condition Systems**, Studies in Informatics and Control SIC Journal, ICI Publishing House, vol. 16(1), 2007, pp.97-114.
4. BOCANIALA, C. D., S. BUMBARU, **Experimental Validation of a Novel Fuzzy Classifier Performance**, Studies in Informatics and Control SIC Journal, ICI Publishing House, vol. 14(3), 2005, pp. 167-180.
5. BENREJEB, M., D. SOUDANI, A. SAKLY, P. BORNE, **New Discrete TSK Fuzzy Systems Characterization and Stability Domain.** International Journal of Computers, Communications & Control, Agora University Editing House - CCC Publications, vol. 1(4), 2006, pp. 9-19.
6. BOUYAHIAOUI, C., L. I. GRIGORIEV, F. LAAOUAD, A. KHELASSI, **Optimal Fuzzy Control to Reduce Energy Consumption in Distillation Columns,** Automation and Remote Control, Springer, vol. 66(2), 2005, pp. 200-208.
7. Dieulot, J. Y., **Fuzzy Control and Estimation Using Model Inversion.** Studies in Informatics and Control SIC Journal, ICI Publishing House, vol. 13(3), 2004, pp. 153-160.
8. DIEULOT, J. Y., P. BORNE, **Inverse Fuzzy Sum-product Composition and its Application to Fuzzy Linguistic**

Modelling. Studies in Informatics and Control SIC Journal, ICI Publishing House, vol. 14(2), 2005, pp. 73-78.

9. GALINDO, J. R. SERRANO, H. CLIMENT, A. TISEIRA, **Experiments and Modelling of Surge in Small Centrifugal Compressor for Automotive Engines,** Experimental Thermal and Fluid Science, Elsevier, vol. 32(3), 2008, pp. 818-826.
10. J. T. GRAVDAHL, O. EGELAND, S. O. VATLAND, **Drive Torque Actuation in Active Surge Control of Centrifugal Compressors**, Automatica, Elsevier, vol. 38(11), 2002, pp. 1881-1893.
11. GRAVDAHL, J. T., F. WILLEMS, B. JAGER DE, O. EGELAND, **Modeling of Surge in Free-Spool Centrifugal Compressors: Experimental Validation**, Journal of Propulsion and Power, Elsevier, vol. 20(5), 2004, pp. 849-857.
12. HAFAIFA, F. LAAOUAD, M. GUEMANA, **A New Engineering Method for Fuzzy Reliability Analysis of Surge Control in Centrifugal Compressor,** American Journal of Engineering and Applied Sciences, Science Publisher Inc, vol. 2(4), 2009, pp. 676-682.
13. HELVOIRT, J. V., B. D. JAGER, **Dynamic Model Including Piping Acoustics of a Centrifugal Compression System,** Journal of Sound and Vibration Elsevier, vol. 302(1-2), 2007, pp. 361-378.
14. MATTONE, R., A. DE LUCA, **Nonlinear Fault Detection and Isolation in a Three-tank Heating System**, IEEE Transactions on Control Systems Technology, vol. 14(6), 2006, pp. 1158-1166.
15. MATTONE, R., A. DE LUCA, **Relaxed Fault Detection and Isolation: An Application to a Nonlinear Case Study**, Automatica, Elsevier, vol. 42(1), 2006, pp. 109-116.
16. MOISE, G., **Applying Fuzzy Control in the Online Learning Systems.** Studies in Informatics and Control SIC Journal, ICI Publishing House, vol. 18(2), 2009, pp. 165-172.
17. NAYFEH, M., E. H. ABED, **High-gain Feedback Control of Rotating Stall in Axial Flow Compressors**, Automatica, Elsevier, vol. 38(6), 2002, pp. 995-1001.
18. PADUANO, J. D., E.M. GREITZER, A.H. EPSTEIN, **Compression System Stability and Active Control**, Annual Review of Fluid Mechanics, Elsevier, (2001), vol. 33, pp. 491-517.
19. POP, B., I. DZITAC, **Fuzzy Control Rules in Convex Optimization.** Studies in Informatics and Control SIC Journal, ICI Publishing House, vol. 15(4), 2007, pp. 363-366.
20. POP, B., I. DZITAC, **Mixed Variables Fuzzy Programming Algorithm.** Studies in Informatics and Control SIC Journal, ICI Publishing House, vol. 16(2), 2007, pp. 185-190.
21. RUDAS, I. J., L. HORVÁTH, **Intelligence for Assistance of Engineering Decisions in Modeling Systems,** Studies in Informatics and Control SIC Journal, ICI Publishing House, vol. 15(3), 2006, pp. 297-306.
22. SPAKOVSKY, Z. S., J. B. GERTZ, O. P. SHARMA, J. D. PADUANO, A. H. EPSTEIN, E. M. GREITZER, **Influence of Compressor Deterioration on Engine Dynamic Behaviors and Transient Surge Margin,** ASME Journal of Turbomachinery, vol. 122(3), 2000, pp. 477-484.
23. ZHANG, X., M. M. POLYCARPOU, T. PARISINI, **A Robust Detection and Isolation Scheme for Abrupt and Incipient Faults in Nonlinear Systems**, IEEE transactions on automatic control, vol. 47(4), 2002, pp. 576-593.