A NONLINEAR MODEL FOR A TURBO COMPRESSOR USING FUZZY LOGIC APPROACH

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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 Control "has been suggested as an alternative approach to conventional control techniques for complex control systems. The objective is to introduce new mechanisms permitting a more flexible control, but especially more robust one, able to deal with model uncertainties and parameter variations. In this work, we examine and illustrate the use of fuzzy logic in modelling and control design of a turbo compressor system. Turbo compressor systems are crucial part of most chemical and petrochemical plants. It's a system being very complex by its physical structure as well as its behaviour (surge problem).

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 control approaches and evaluate their contribution in the practical and theoretical fields consequently. Facing to the studied industrial process complexity, we choose to make recourse to fuzzy logic for analysis and treatment of its control 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. In the particular case of the turbo compressor, these imperfections are interpreted by modelling errors, the neglected dynamics and the parametric variations.

Fuzzy logic intervene efficiently in the compressor modelling. The fuzzy logic model suggested in this work reproduced well the main characteristics of the turbo compressor dynamic model developed by Gretzer and Moore and give place to a more precise and easy to handle representation. It is about a inaccuracies reproducing with a certain degree of satisfaction of the real process without being as much complex .

Keywords
Compresseur, Fuzzy logic, Surge control, modeling, Stability analysis, Nonlinear plant.

Nomenclature

Ac Flow area
as Speed of sound
B Greitzer parameter
J Squared amplitude of rotating stall
m Compressor duct flow parameter
Vp Plenum volume
W Compressor characteristic semi-width
γ_T Throttle gain
γ_V CCV gain
Φ Mass flow coefficient
Ψ Pressure coefficient

1. Introduction

A compressor transfers kinetic energy from an aero-mechanically-driven rotor to a steady flow of gas. The pressure of the gas is raised by converting the acceleration imparted by the rotating parts of the compressor via diffusion. In normal operation of a compressor, the flow is nominally steady and axisymmetric. The pressure rise is dependent on the speed of rotation, but the efficient range is limited. As the flow through the compressor is throttled from the design point to the stall limits, the steady axisymmetric flow pattern becomes unstable. This instability can take on one of two forms, either surge or rotating stall depending upon the compressor speed. The performance of a compressor is plotted as pressure ratio versus mass flow for different rotational speeds. The plot is divided into two regions by the stall (or surge) line. This line defines the operation limits of the compressor. To the left of the stall line the flow is no longer steady. In this region large oscillations of the mass flow rate may occur (surge) or severe selfinduced circumferential flow distortions may rotate around the annulus (rotating stall), or a combination of both may appear **[6]**.

Surge in centrifugal compressors cannot, in general, be avoided when a unit trip or a major upset occurs, but the energy of surge should be minimized. Surge is a dramatic collapse of flow within a centrifugal compressor, which results in reverse flows within the machine and attached piping and can cause damage to bearings and other components.

During normal and slowly changing operations, surge can be avoided by recycling gas through the surge control valve to maintain a minimum flow **[8]**. However, when a trip or major upset occurs, flow rate drops and the primary means by which surge energy can be reduced is to lower the head (suction to discharge pressure difference) at which the compressor reaches the surge (minimum stable) flow condition. The head across a compressor during a trip or upset is dependent on the response of the entire system including changing performance of the compressor, transient flows within the piping, control system responses, and capacity and opening rate of surge and other automatic valves, such as vent or blow down valves, and check valves.

This paper describes tools and techniques that can and have been used to model transient flows and performance, mechanical and control responses, and time dependent head in compressor systems. The tools used by fuzzy logic include a method of characteristic transient flow analysis routine and finite time step programs that simulate control systems, valve actuators, and the opening (or closing) rate of valves with the resulting flows. The effects of volumes and lengths of station piping, scrubbers, and coolers including temperature effects are accounted for. Fuzzy logic models also track the performance of centrifugal compressors at different speeds, account for the rotation inertia of compressor trains, and evaluate the thermophysical properties of gas streams.

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. 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 **[1]**.

2. Fuzzy modeling

2.1 Fuzzy logic – basic principles

Fuzzy logic is a generalization of yes-no Boolean logic. Assigning to false values and to true ones, fuzzy logic also allows in-between values.

Assuming that U is a set of values of fuzzy logic defines a mapping from U to the unit interval through a membership function $\mu_A(u): U \to [\,0,1\,]$ **[9]**. This membership function can be defined in linguistic terms. As it can be seen in figure 1, the subjective feeling of surge as a result of a mass flow coefficient and pressure coefficient, is not defined in a crisp sense as surge or as an *Intolerable surge* - it is defined as *0.5* surge and *0.5 Intolerable*. In this way, the uncertainty present in every systems can be implicitly represented **[7]**.

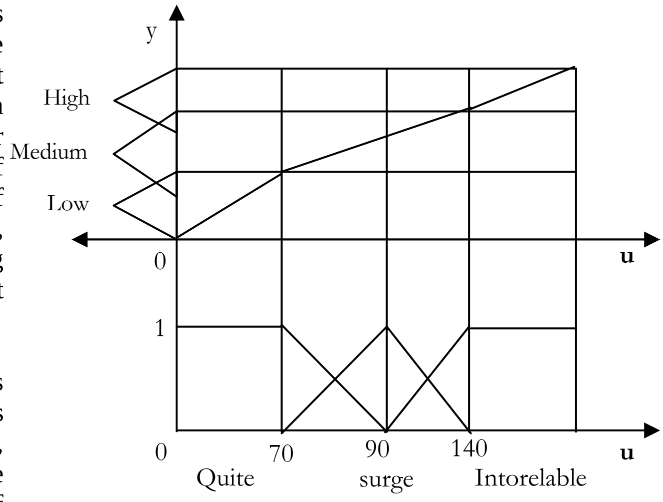

Fig1: Linguistic fuzzy model

2.2 Fuzzy models

Fuzzy models are flexible mathematical structures that, in analogy to nonlinear model, have been recognized as universal function approximators **[11]**. 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 the surge and the 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 (1)

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.

2.3 Fuzzy model type Takagi-Sugeno (TS)

Takagi and Sugeno **[10]** 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:

$$R_i \ : IF\ u\ \ is\ \ A_i \ \ THEN\ \ y = f_i\ (u)\ , i = 1, \ldots , K \quad (2)$$

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 ith 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 :

$$R_i : IF\ u\ \ is\ A_i\ THEN\ \ y = a_i^T u + b_i\ \ , i = 1, \ldots , K \quad (3)$$

where a_i is a parameter vector and b_i is a scalar offset. Figure 2 presents an example of a TS model.

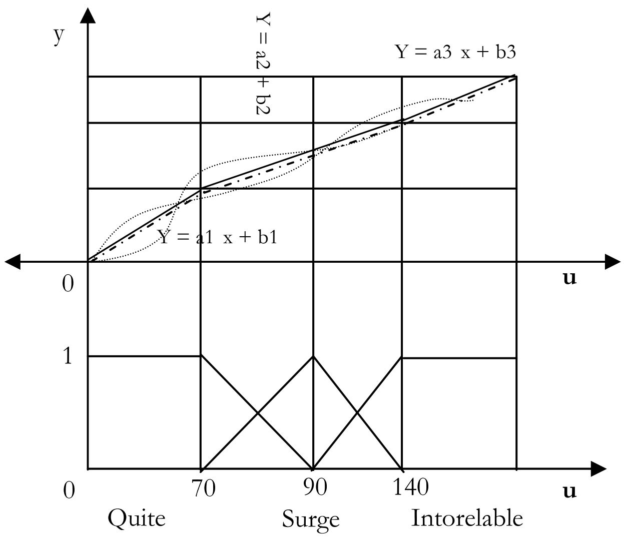

Fig 2 : Fuzzy TS model with clustering

3. Fuzzy model of compression system

The fuzzy logic model is a rule-based system that receives information fed back from the plant as it operates, in this case the normalized fluctuations of Φ and Ψ. These crisp values are fuzzified and processed using the fuzzy knowledge base **[2]**. 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 drawn upon to modeling the control system. Increasing either the throttle or CCV control gains 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 **[4]** :

$$\Delta\Psi_i = \frac{\left| \Psi_i - \Psi_{i+\Delta t} \right|}{Max(\Psi_i , \Psi_{i+\Delta t})} \quad (4)$$

$$\Delta\Phi_i = \frac{\left| \Phi_i - \Phi_{i+\Delta t} \right|}{Max(\Phi_i , \Phi_{i+\Delta t})} \quad (5)$$

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 **[3]**. The crisp output from the fuzzy model adjusts both control gains by the following :

$$\gamma_{i+\Delta t} = \gamma_i + \gamma_i\, \Delta\gamma_i \quad (6)$$

Triangular membership functions are defined for each classified category of input and output as shown in Table 1. The base of each triangular membership function rests on the intervals of each category, and the apex of the triangle is located above the midpoint of the interval.

Table 1
Operating ranges of fuzzy inputs and output

$\Delta\Psi$ and $\Delta\Phi$	
Low	0.00 - 0.25
Medium	0.25 - 1.00
High	0.50 - 1.00
$\Delta\gamma_V$ and $\Delta\gamma_T$	
Low	0.00 – 0.30
Medium	0.30 – 0.75
High	0.75 – 1.00

3.1 Constructing the Rule Base

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 (see Table 2). The entries in the matrix are the desired response of the system, the changes in either throttle or CCV gain.

Table 2
Rule base matrix for two input - one output system

$\Delta\Psi$	$\Delta\Phi$		
	Low	**Medium**	**high**
Low	Low	Low / Medium	Low / medium
Medium	Low / Medium	Medium	Medium / High
High	Low / High	Medium / High	High
	$\Delta\gamma_V$ and $\Delta\gamma_T$		

From Table 2 a rule base of three rules can be created (one for each entry along the diagonal).

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]

4. Simulation Results

The results of two simulations are presented in this section. The first is the comparison between the complex model, the linearized model and the fuzzy model suggested with Greitzer parameter $B = 1.50$, and the second simulation is the comparison between the complex model, the linearized model and the fuzzy model suggested with Greitzer parameter $B = 0.50$. For both simulations the value of J, the squared amplitude of rotating stall was set to zero, and the throttle gain was set so that the intersection of the throttle line and the compressor characteristic is located on the part of the characteristic that has a positive slope.

The response of the system with comparison is shown in Figure 3 for the mass flow coefficient for $B = 0.50$, the response of the system with comparison for the pressure coefficient for $B = 0.50$ is shown in figure 4. Both simulations push the design point along the compressor characteristic until it reaches a stable operation point without overshooting a stable equilibrium point. An overshoot of the equilibrium conditions would result in pressure lost across the throttle.

The response of the system with comparison is shown in Figure 5 for the mass flow coefficient for $B = 1.50$, the response of the system with comparison for the pressure coefficient for $B = 1.50$ is shown in figure 6.

According to the above figures, we can notice that our fuzzy logic model is very reliable since its outputs match those of the nonlinear complex model with a very small error in a short time interval for the open loop response, hence the obtained model can be used for the output prediction or for the compressor control.

According to the obtained results it appears clearly that the characteristics of the system of compression describes by the complex model reproduced perfectly by the fuzzy logic model.

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 control purposes. The fuzzy logic method is a recent method that satisfies the requirements sited above. 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.

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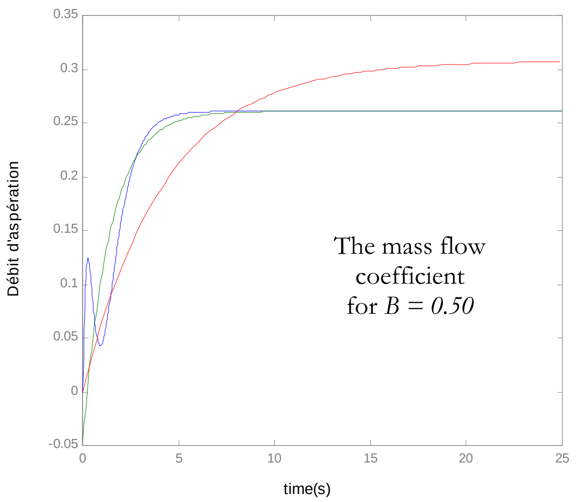

Fig 3 : Comparison between :
the linearized model
the fuzzy model

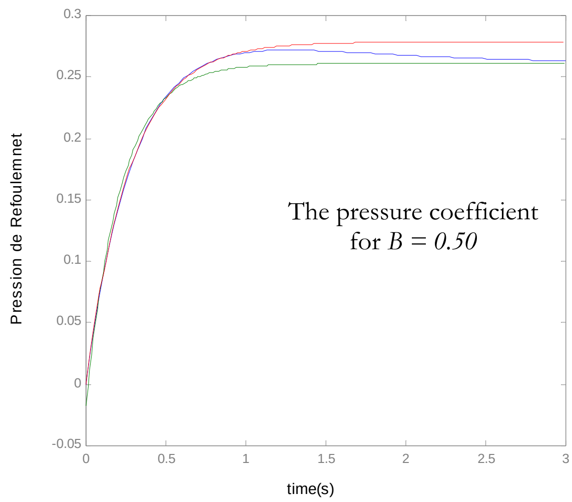

Fig 4 : Comparison between :
the complex model
the linearized model
the fuzzy model

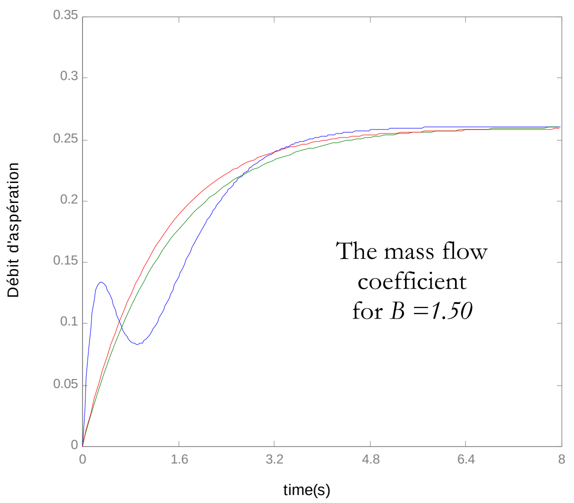

Fig.5: Comparison between :
the complex model
the linearized model
the fuzzy model

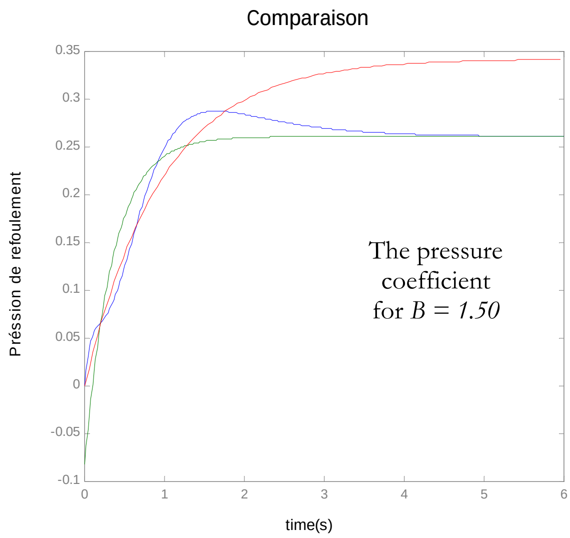

Fig. 6 : Comparison between :
the complex model
the linearized model
the fuzzy model