Fuzzy modeling and identification of intelligent control for refrigeration compressor

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Fuzzy modeling and mathematical analysis for the intelligent control of compressor in order to regulate refrigerant mass flow in vapour compression refrigeration system has been described. The compressor speed and delivery pressure are taken as input parameters and mass flow rate is considered as output parameter. To develop an effective model for control design, fuzzy rule base is designed with and without sub clustering. Intelligent control is used to receive the input signal and generate the output signal to control the mass flow rate from the compressor. Swept volume, suction pressure and densities are considered as fixed parameters.

Keywords: Adaptive neuro-fuzzy inference system (ANFIS), Clustering, Fuzzy control, Refrigeration compressor, Sugeno fuzzy inference system

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Introduction

Fuzzy logic theory is one of the most innovative, active and fruitful areas of research for science and engineering applications, especially in the field of industrial processes1. Fuzzy set theory is used to analyze the engineering applications and to control the difficult to control systems with great ease, which gives a considerable approximation of the parameters of mathematical functions2. MATLAB environment is used for modeling, identification and validation of system under consideration3. Fuzzy systems have been successfully applied to problems in classification, modeling control4,5 and in a considerable number of applications.

Compressor is widely used in the field of refrigeration, air-conditioning and chemical engineering, as it is most important part of the vapor compression cycle. The calculation accuracy of the performance of compressors is important to optimal designing of refrigeration using compressors. By the fuzzy approach, the system input/output relationship can be obtained from the system input/output samples1,2. The classical thermodynamic model of calculating thermal performance of refrigeration compressors has been widely used. The fuzzy method was introduced to predict the performance of refrigeration compressors. Study shows that fuzzy method can produce better effect than the classical thermodynamic method. Some problems hard to be treated by classical methods may be solved in this way6. It has also been attempted to control the phase of the working fluid and stroke of the linear compressor with dual fuzzy controller7.

In the present paper, a systematic control design method based on fuzzy modeling (FM) using sugeno fuzzy inference system and adaptive neuro-fuzzy inference system (ANFIS) has been presented. For the purpose of control design of the compressor mass flow rate, fuzzy rule base is designed with and without sub clustering. Swept volume, suction pressure, density at evaporator entry is taken as fixed parameters.

Compressor Model

Compressor, most complex component in vapor compression refrigeration, compresses low-pressure vapor refrigerant into high pressure such that high-pressure refrigerant can condense in a condenser to reject the heat to the second fluid (Fig. 1). It is assumed that the compressor wall is well insulated from the ambient air.

Generally, the mass flow rate (MFR) is dependent on compression ratio, compressor speed (CS) and density of the refrigerants. The CS was taken into
Mathematical modeling gave the behavior of the response of MFR with respect to CS, delivery pressure (DP) and suction pressure. In present study suction pressure is kept fixed at one bar.

**Fuzzy Logic in Compressor**

Fuzzy logic (FL), which reflects qualitative and inexact nature of human reasoning, makes it possible to cope with uncertain and complex systems, which are difficult to model mathematically. The method is a way of transforming situations into a form, where decision-making rules can be applied. Essentially, imprecision is handled by attaching measures of credibility to propositions. By using FL, a powerful system can be achieved that takes many factors into account without incurring undue complexity. FL is a convenient way to map an input space to an output space.

**Sugeno Type Fuzzy Inference System**

Sugeno type fuzzy inference based system is taken for the FM and control of the compressor parameters. ANFIS editor is used to create, train and test the sugeno fuzzy system. This technique provides a method for FM procedure to learn information about a data set, in order to compute the membership function parameters that best allow the associated fuzzy inference system to track the given input/output data. This learning method works similarly to that of neural networks.

The membership functions parameters are tuned using a hybrid system that contains the combination of back propagation and least squares type method. This allows fuzzy systems to learn from the data they are modeling. The parameters associated with the membership functions will change through the learning process. The computation of these parameters is facilitated by gradient vector, which provides a measure of how well fuzzy inference system is modeling the input/output data for a given set of parameters. Once the gradient vector is obtained, any of the several optimization routines could be applied in order to adjust the parameters so as to reduce some error measure.

**Input and Output Variables**

This study defines multi input single output (MISO) system with two input parameters and one output parameter. The CS and DP variations are taken as input variables and MFR is taken as output variable. Three major functional blocks (Fig. 2), used for fuzzy system, are: Fuzzification (FF); Inference engine (IE); and Defuzzification (DF). FF block
transforms a real signal into the appropriate fuzzy set, the IE leads to a fast, flexible and unified computer implementation algorithm and the DF produces a real signal from fuzzy variables. This is essentially the reverse operation of the FF process. The center of area (COA) method is used. For FF, it is essential to identify the process variables in actual Universes of Discourse (UOD), which is the range of values that a variable may take. UOD may be actual (measured) and computational. The following are the range of values for the input (CS, DP) and output (MFR) parameters: CS, 100-1500 rpm; DP, 6-16 bar; and MFR, 0-550 kg/min.

**Design of Fuzzy Rule Base for Compressor Control**

The selection of rule base is based on the designer's experience and beliefs on how the system should behave. For design of a rule base, linguistic rules (surface structure) are set and then membership functions of the linguistic values (deep structure) are determined. The trade-off involving design of the rule base is to have a set of minimum number of linguistic rules representing the control surface with sufficient accuracy to achieve an acceptable performance. Recently, some formal techniques for obtaining a rule base by using artificial neural networks or genetic algorithms have appeared. Usually, to define the linguistic rules of a fuzzy variable, gaussian, triangular or trapezoidal shaped membership functions are used. Selection of gaussian like membership functions leads to smoother control surfaces. Fuzzy Input variables (CS & DP) are divided into linguistic levels membership functions, which are decided with and without sub clustering (Figs 3 & 4).

The tuning of the fuzzy rules is intuitive, and can be related in simple linguistic terms with user's experience. It should be a straightforward matter to achieve an appropriate balance between a tolerable end-to-end delay, and the increase in throughput. Alternatively, an adaptive fuzzy logic control method can be used which can tune the parameters of the fuzzy logic controller on line, using measurements from the system.

Differential equations are the base of conventional control; in the similar way IF-THEN rules to control the process/operation are the bases of fuzzy control. Fuzzy rules serve to describe the qualitative relationship between variables in linguistic terms. If a fuzzy system has n inputs and single output, then its fuzzy rules can be of the following general format:

If \( X_1 \) is \( A_{ij} \) and \( X_2 \) is \( A_{ij2} \) and \( X_3 \) is \( A_{ij3} \), \( \ldots \ldots \), \( X_m \) is \( A_{ijm} \) then \( Y \) is \( B_j \).

where, \( A_{ij} \) are the fuzzy sets of the input linguistic variable \( X_i \) and \( B_j \) is called the set of the output linguistic variable \( Y \). The process is already defined as MISO system. Several rule bases of different complexity have been developed for the controller.

Set of linguistic rules using sub clustering are (Fig. 5a):

(i) If speed is in1mf1 and DP is in2mf1 then MFR is in out1mf1.
(ii) If speed is in1mf2 and DP is in2mf2 then MFR is in out1mf2.
(iii) If speed is in1mf3 and DP is in2mf3 then MFR is in out1mf3.
(iv) If speed is in1mf4 and DP is in2mf4 then MFR is in out1mf4.
(v) If speed is in1mf5 and DP is in2mf5 then MFR is in out1mf5.
(vi) If speed is in1mf6 and DP is in2mf6 then MFR is in out1mf6.
(vii) If speed is in1mf7 and DP is in2mf7 then MFR is in out1mf7.
(viii) If speed is in1mf8 and DP is in2mf8 then MFR is in out1mf8.
(ix) If speed is in1mf9 and DP is in2mf9 then MFR is in out1mf9.

![Functional blocks showing input and output variables for fuzzy control system](image-url)
Fig. 3a — Input membership functions (compressor speed) with subclustering

Fig. 3b — Input membership functions (delivery pressure) with subclustering

Fig. 4a — Input membership functions (compressor speed) without subclustering

Fig. 4b — Input membership functions (delivery pressure) without subclustering
(x) If speed is in1mf10 and DP is in2mf10 then MFR is in out1mf10.

(xi) If speed is in1mf11 and DP is in2mf11 then MFR is in out1mf11.

(xii) If speed is in1mf12 and DP is in2mf12 then MFR is in out1mf12.

Set of linguistic rules without subclustering are (Fig. 5b):

(i) If speed is in1mf1 and DP is in2mf1 then MFR is in out1mf1.

(ii) If speed is in1mf1 and DP is in2mf2 then MFR is in out1mf2.
(iii) If speed is in1mf1 and DP is in2mf3 then MFR is in out1mf3.
(iv) If speed is in1mf2 and DP is in2mf1 then MFR is in out1mf4.
(v) If speed is in1mf2 and DP is in2mf2 then MFR is in out1mf5.
(vi) If speed is in1mf2 and DP is in2mf3 then MFR is in out1mf6.
(vii) If speed is in1mf3 and DP is in2mf1 then MFR is in out1mf7.
(viii) If speed is in1mf3 and DP is in2mf2 then MFR is in out1mf8.
(ix) If speed is in1mf3 and DP is in2mf3 then MFR is in out1mf9.

Control Surface for Compressor Control
The designed fuzzy rule base gives the control action surfaces with and without sub clustering (Fig. 6). It is the surface, which gives the interdependency of input, and output parameters guided by the various rules [9 rules (without sub clustering) and 12 rules (with sub clustering)] in the given universe of discourse and define the control actions. These rules were implemented in MATLAB environment using Sugeno type of fuzzy inference system on ANFIS editor.

Validation of Fuzzy Model
After extensive sorting of the Eqs (1-5), a complete graphical interdependency of the mathematical model was obtained for the MFR, DP and CS (Fig. 7). Further, design of control rules base is finalized with proper choice of IE, membership functions, FF and DF techniques. Model program was written in fuzzy logic toolbox in the environment of MATLAB. CS and DP were designated as input of the program and refrigerant MFR as output of the program. FM based analysis has been taken to know MFR by varying the DP and CS in respective universe of discourse. Behaviors of parameters from FM techniques with and without sub clustering were depicted (Figs 8&9).
Results obtained from FM are very close to that of mathematical model (Table 1). The curves got from mathematical model and FM at different delivery pressures (6, 8, 10, 14, 16 bar) are very much overlapping and seems to be one as these are one above the other (Fig. 10). So, FM is validated and this supports the use of fuzzy logic in controlling the MFR with CS and DP, as it is very easy to handle non-linear situations with the use of fuzzy model than mathematical model, as no explicit input-output equations are available and readily applicable to control design.

**Conclusions**

Compressor model was identified for compressor speed and delivery pressure as input parameters and refrigerant flow rate as output parameter. For these parameters, FM was established to predict MFR in
vapour compression cycle. The Fuzzy rule base of undertaken MISO control system was designed with and without subclustering technique and the results were very close with mathematical modeling analysis for CS and DP variations. With this FM, nonlinear behavior of the various parameters such as CSs, evaporator pressure (fixed in present study) and DPs were identified and controlled to regulate the refrigerant MFR. The model is expected to be very useful in making appropriate control system for compressor used in vapor compression refrigeration system.

References

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